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JOHN DUER IRVING.

TO HIS MEMORY.

With deepest sorrow we announce the death of John Duer Irving, editor of ECONOMIC GEOLOGY since its first appearance in 1905. He died in the line of duty, on July 20, while serving as captain in the 111th Engineer Regiment with the Expeditionary Force in France.

His friends and all those who are interested in geological science will receive this message with grief and regret, for in Irving was combined as in few men a lovable nature, strength of character and deep learning. No one will dispute his position as one of the foremost representatives of applied geology in this country. Tempering our sorrow is only the knowledge of success achieved despite the brief span of life, and of a death in the service of his country.

In 1916, he was one of the first that joined the Plattsburgh camp; while there he obtained the rank of sergeant. In 1917 he was appointed captain and left with one of the early contingents for France. At first engaged in railroad work during which he came under shell fire with his regiment, he was later detailed as instructor in a school of mining and engineering as applied to warfare. The hard work and his unremitting attention to duty told at last. A slight attack of influenza turned into pneumonia,

and in spite of all that could be done he passed away near midnight, July 20.

Major Alfred H. Brooks tells us in a letter of the impressive ceremony as Irving's body was laid to rest with military honors in the American cemetery on the sunny slopes below the old town and adds that "these last rites were not performed simply as an official duty, but all who took part had a strong sense of personal loss, for Irving was admired and liked by all who knew him. He worked in the military service, as he has always in civil life with the one end, the accomplishing of results with no thought of self. Finally, worn out, he died after accomplishing much." His last task consisted in elaborating the methods of designing and constructing shelters, a work by which sanitary conditions will be improved and many lives saved.

A descendant of a distinguished family, Irving was born August 18, 1874, at Madison, Wis. At his death he had thus not quite reached his forty-fourth birthday. He was the son of Roland Duer Irving, professor of geology at the University of Wisconsin, who also died in early manhood, though not before he had won fame as one of the pioneers of petrography in this country. Undoubtedly he implanted in his son, at an early age, a love for geology. The boy resolved to carry forward the work of his father.

John Duer Irving took up his professional studies at Columbia University, quite naturally so, for it had been the alma mater of his father and his grandfather. At Columbia he found a mentor and a life-long friend in Professor J. F. Kemp, under whose guidance he completed his studies, obtaining the degrees of bachelor of science in 1896, master of science in 1898, and doctor of philosophy in 1899. His thesis consisted of an account of geological work in the Black Hills of South Dakota.

The service of the U. S. Geological Survey proved a strong attraction for a young man intending to devote himself to applied geology, and for the next few years after obtaining his doctor's degree, Irving worked in this organization, first as geologic aid and from 1900 to about 1910 as assistant geologist, though he left the active service in 1903 to engage in teaching.

His first work carried him to the San Juan region of Colorado under Whitman Cross. Later he pursued more directly practical work in mining geology under S. F. Emmons, than whom there was no more distinguished instructor. Irving proved himself an apt pupil and Emmons' appreciation and friendship were evident by his selection of Irving as his coadjutor in preparing of a report on the ore deposits of the Black Hills of South Dakota, including the famous Homestake Mine. This was published in 1904. In 1905 he wrote on the ore deposits at Ouray, Colorado. He was a co-author of the Ouray and Needle Mountain Folios, in which parts of the San Juan region are mapped. Other work carried him to Arizona and again to Colorado. With Howland Bancroft he wrote in 1911 a notable report on the Lake City mining district in the latter state.

Emmons also enlisted the assistance of Irving in the revision of the well-known report on the Leadville mining district, Colorado. In 1907 appeared a bulletin of the U. S. Geological Survey entitled: "The Downtown District of Leadville," in which the geology of that part of Leadville was portrayed with great exactness in many careful sections. The plans for a revision of the Leadville report by the U. S. Geological Survey were interfered with by Emmons' death in 1911. Though heavily burdened with other duties Irving from a strong sense of loyalty to Emmons' memory decided to take up the completion of this work which was to occupy a large part of his spare time almost to the time of his death. It was a peculiarly difficult undertaking, for it had been decided to construct geological plans and sections with a degree of exactness hardly ever before achieved in mining geology. This involved an enormous amount of detailed work, and as was his custom, Irving refused to do anything in a superficial manner. Most valuable general results as to faulting and structure and mineralogy were achieved, but the preparation of the report, which now is in the hands of the U. S. Geological Survey, almost exhausted Irving's great patience and strength. On July 7, just two weeks before his death, he penned a letter to the writer containing these pathetic lines: "This [the Leadville report] has been a millstone for many years and I shall now—war

or no war—be a free man . . . quite a different person from the one you have known."

In the meanwhile, still following in his father's footsteps, he decided to take up teaching. The personal element, the idea of service to the young generation appealed to him. He served one year (1903) in the University of Wyoming at Laramie, later was appointed professor of geology at Lehigh University, and in 1907 was called to the chair of economic geology at the Sheffield Scientific School at Yale University, a position which he occupied until his death. His patience as well as his great knowledge and delightful personality made him a most successful teacher and a great number of young geologists owe their success to their personal contact with Irving in his graduate teaching. He did not escape the wearing task of elementary teaching and this as well as his editorial duties tended to interfere with his research work. As a teacher he applied the methods of petrography to ore deposits, and also gave much attention to the influence of structural features, a tendency emphasized by his deep studies of faulting at Leadville.

Many other subjects crowded his short life. In 1911 he wrote a long paper on "Replacement Ore Bodies and the Criteria for their Recognition," which was published by the Canadian Mining Institute, by the American Institute of Mining Engineers, and by ECONOMIC GEOLOGY. In this paper his long studies bore fruit and the result is a masterly treatise of the subject of replacement, which attracted attention among geologists all over the world. At times Irving also undertook geological investigations for private corporations; this work, which helped materially to broaden his views, carried him to Canada, Alaska and many parts of the United States.

But it is my purpose to dwell more strongly and with loving remembrance on his work as editor of ECONOMIC GEOLOGY, a journal which has done more than any other private agency to advance the study of applied geology to the strong position which it occupies today in this country.

One day in 1905 a small group of geologists met at the Cosmos Club in Washington to discuss the possibility of establishing a

medium of exchange of opinion and a place where short papers on subjects relating to the genesis of ore deposits could be discussed. Spurr, I believe, was one of the first to advance the suggestion. It was received with great approval but also with some doubt as to the possibility of success. Finally a stock company was formed and the founders received handsome certificates which indicated a financial sacrifice upon the altar of science. The next question was, who was to be the editor? It must be a hard worker and an unselfish man, a man willing to do much work for nothing, for the conditions of the company allowed then no recompense for such work, and has not done so for thirteen years. The writer of this proposed Irving as editor and he was partly instrumental in persuading him to accept. He admits this with strangely mixed feelings, for ever since some of the men of that group have felt that by that action they perhaps laid too heavy a burden on a fellow worker, a burden which once assumed he would not give up in the face of difficulties. The first years were hard. Papers were scarce and financial conditions doubtful. Conditions gradually became better and the journal became self-sustaining, but only because of the unselfishness of the editor. No one but those who were associated with Irving could appreciate the hard work, the drudgery and the worry connected with the enterprise. Perhaps no one knows it better than Professor W. S. Bayley, who as the business editor of the journal for these thirteen years has given equally freely of his scant spare time. But there was also the note of joy for success crowned the efforts. The journal became an acknowledged leader of applied geology and the papers published in its files constitute a record of the world's best work in this line. One need not look far in the pages of the journal to see the marks of Irving's personality. Many are the useful discussions on field methods, reports, ore shoots, etc., that Irving originated. Without wanting to do so, he has reared an enduring monument to his memory in these thirteen volumes of our journal.

It is a difficult matter to sum up a personality in a few poor words. Tall of stature he was, strong of feature, yet with an indescribable touch of delicacy and gentleness, modest and un-

assuming in bearing. We remember his slight stoop, the knitted brows when his thoughts were busy; we remember his whimsical humor so frequently directed against some of his own little shortcomings; we remember how his face lit up with that irresistible smile; we remember him as the scientific man who always wanted to go to the heart of the problem; as a sure, though not a rapid worker; as a teacher whose patience and lucidity were remarkable; as a man in whom were personified honor, sense of duty and courage. One of his fellow officers expressed well the feelings of many when he said in a letter written July 21 that "my previous admiration for his ability and personality have deepened into the highest respect and affection for him as a friend, superior officer and man."

And so, John Irving, among darkening shadows you had to take the last trail and cross the Great Divide! We bid you farewell—loving brother and friend, distinguished investigator, faithful editor and teacher, gallant soldier—Chevalier sans peur et sans reproche.

WALDEMAR LINDGREN.

ON THE MICROSTRUCTURE OF CERTAIN TITANIC IRON ORES.

CHARLES H. WARREN.

Notwithstanding the very considerable amount of study that has been carried out on the "Titanium-iron-oxide minerals," there is still much uncertainty regarding the true constitution of this group of minerals. With a view of extending somewhat further our knowledge of these minerals, the writer and one of his former students[1] undertook a study of selected specimens from a number of localities. The results of this study follow, and while they, perhaps, serve chiefly to point out the complexity of the problems connected with the constitution of these minerals, it is felt that they, at least, add something of value to our knowledge of the micro-characters of the titanium-iron-oxide minerals.

It will be recalled that Mosander[2] made the first analyses of "titanic irons" and concluded that they consisted essentially of the compound $FeTiO_3$ (with MgO and MnO) mixed with Fe_2O_3, implying thereby that these were isomorphous. H. Rose contended that this could not be so, that the titanium was really present as Ti_2O_3, and might be isomorphous with Fe_2O_3. He and others held that the FeO shown by the analyses was the result of a reaction between Fe_2O_3 and Ti_2O_3 during the decomposition of the mineral. Rammelsberg,[3] as a result of a classic investigation on the composition of "titanic iron ores," concluded that Mosander's formula was correct. He pointed out that MgO was always present and, in certain cases, that it amounted to as much as 15 per cent. of the whole. In view of this it seemed necessary

[1] Mr. W. F. Pond (now Captain of Engineers, R.C.), who was called to the colors shortly afterwards. Mr. Pond's departure has made it impossible to carry out at this time certain experimental and chemical work that had been planned.

[2] *Pogg. Ann.*, 1830, 19, 211.

[3] *Pogg. Ann.*, 1858, 104, 503–552.

to assume that the molecule $MgTiO_3$ was present and it seemed most reasonable to assume that this was isomorphous with the iron-bearing molecule $FeTiO_3$. He, therefore, assigned the formula $RTiO_3$ to ilmenite. He recognized that there were certain varieties which showed such a composition that it seemed necessary to assume the presence of such molecules as $Fe_2(TiO_3)_3$; also that certain titanic irons were probably magnetites, and that possibly Ti_2O_3 in these replaced Fe_2O_3. He also suggested that some were simply ordinary mixtures of the two minerals. Many years later Penfield and Foote[4] came to the same conclusion regarding the correctness of the $RTiO_3$ formula. Groth[5] considers that Ti_2O_3 is isomorphous with Fe_2O_3 in certain titaniferous hematites. He looks upon the "Titaneisenerz" as in part represented by the formula $FeTiO_3$, but in part also containing Fe_2O_3, possibly as an isomorphous mixture, though he questions the propriety of considering them isomorphous on acocunt of their differences in formula and crystallization, but in accordance with his views, prefers to consider them as "molecular intergrowths."

The chemical analyses, though numerous, and many of them excellent, are not in themselves competent to settle just what the true constitution of the ilmenites and "titanic iron ores" are. Further experimental work on the equilibrium relations of the oxides of iron and titanium must be carried out as well as further microscopic studies of these minerals before anything like final answer can be given. The present study is a step in furnishing the needed microscopic evidence.

O. Mügge,[6] in his paper on the regular intergrowths of minerals of different kinds, gives an excellent summary, with bibliography, of the earlier work relating to the parallel growths and intergrowths of ilmenite, hematite and the spinels. Becke, Cathrein, Rosenbusch and Hussak in particular have noted intergrowths of ilmenite and magnetite. The writer has also de-

[4] *Am. Jour. Sci.* (3), Vol. 4, 1897, p. 108.
[5] Tabellarische Übersicht, 1898, p. 45.
[6] *Tschermak's Min. pet. Mitt.*, B. B. 16, 1903.

scribed an intergrowth of magnetite and ilmenite[7] and also one of hematite and ilmenite.[8] Mr. J. T. Singewald[9] has described in detail intergrowths of magnetite and ilmenite in many American titanic iron ores.

The present study includes a number of ilmenites, etc., not previously studied microscopically, together with a reëxamination of certain ones that have been so studied.

The microscopic study was carried out on a large model Leitz, metallographic microscope, using a small four-ampere arc as a source of light.

The writer wishes, in this place, to express his thanks to Professor Charles Palache, of Cambridge, Massachusetts, for several specimens kindly loaned to him for study from the Harvard University collections, and to Professor William E. Ford, of New Haven, Connecticut, for a crystal of the Warrick, New York, ilmenite, described by Penfield and Foote.

Ilmenite from Miask, Ural Mountains, Russia.—The material studied was taken from a large crystal collected at the original locality by Professor Charles Palache, of Cambridge, Mass. It occurs in pegmatite, and though of rough exterior, shows clearly the characteristic crystalline form of ilmenite. It has a nearly black streak and is non-magnetic.

Ilmenite from this locality has been studied by several and analyses are recorded by Rose, Mosander, Rammelsberg and others. Three by Rammelsberg[10] are apparently the most reliable. There is some variation among them, as might be expected from materials differing in specific gravity (4.811, 4.833, 4.873). A recent analysis by Doby and Melzer[11] departs very widely from the others in the ferrous and ferric iron values, and yields no simple ratio, however figured.

The mean of Rammelsberg's analyses is as follows:

[7] *Am. Jour. Sci.* (4), Vol. 33, March, 1912.
[8] *Am. Jour. Sci.* (4), Vol. 25, Jan., 1908.
[9] Bull. 64, U. S. Bureau of Mines, 1913.
[10] *Op. cit.*, p. 513.
[11] *Zs. für Kryst.*, Bd. 39, p. 540, 1904.

	Per Cent.	Molc. Ratio.	Ilm.	Fe_2O_3.	TiO_2.
TiO_2	45.93	.573	.548	.089	.025
Fe_2O_3	14.30	.089			
FeO	36.52	.495	.548		
MnO	2.72	.038			
MgO	.59	.015			
	100.06				

Rammelsberg interpreted this analysis as indicating that the mineral consisted of $RTiO_3$ isomorphously mixed with Fe_2O_3. This is a reasonable interpretation but it may be noted that there appears to be an excess (2.20 per cent.) of TiO_2.

Polished surfaces show this material to be entirely homogeneous. The color under the conditions of illumination used may be described as a light, somewhat reddish brown. The purity and homogeneity of this ilmenite suggest that it may well be taken as a type.

Ilmenite from the Ilmenite-Nelsonite, Nelson County, Virginia.—This interesting rock has been described by Dr. T. L. Watson and Stephen Taber.[12] They have given an analysis by W. M. Thornton of the ilmenite separated from the rock, which is as follows:

SNARUM.

	Per Cent.	Molc. Ratio.	Ilm.	R_2O_3.	TiO_2.
TiO_2	54.44	.680 .686	.577		.103
SnO_2	tr.				
SiO_2	.34				
Fe_2O_3	4.26	.027			
Cr_2O_3	.07	.001 .030		.030	
V_2O_3	.29	.002			
Cb_2O_3	None				
Ta_2O_3	None				
FeO	40.94	.570 .577	.577		
MnO	.52	.007			
H_2O	None				
	100.86		87.49	.480	8.32

Sp. gr. 4.713.

The excess of TiO_2 is notable; the hematite is low.

Under the microscope polished surfaces appear to be homoge-

[12] Bull. III., *A*, Virginia Geol. Survey.

neous with the exception that there are present a few very narrow straight bands, often crossing at definite angles, of lighter color than the ilmenite which is of the same color as the Miask type. This is probably hematite or perhaps rutile, it being difficult to decide with such narrow bands. Whichever it may be, the total amount represented by it is small and it is clear that either there is rutile present in such a fine state of division that it cannot be detected microscopically or that there is a notable amount of solid solution between the ilmenite and rutile or whatever titanium-rich molecule is present. The rutile bearing-ilmenite-nelsonite described by Watson shows its rutile in perfectly distinct grains.

Arendal, Norway.—The material studied was part of a large crystal showing the characteristic ilmenite habit, color black but not so lustrous as that from Miask, fracture less strongly conchoidal, streak nearly black, rather strongly magnetic. The crystal was polished parallel to the base and under the microscope with high powers appeared as a substantially homogeneous material of a pale delicate brownish or purplish red (perhaps somewhat less red than the Miask ilmenite) although absolute comparison of these colors is difficult.

This substance is crossed by faintly marked, narrow bands of slightly lighter color, evidently magnetite, running through the ilmenite at rather frequent intervals. These appear to run parallel to the trace of a rhombohedral plane. The magnetic property of this ilmenite may well be due to the presence of this magnetite, though it is, of course, possible that it is also due to other causes.

Two analyses of ilmenite from Arendal are recorded by Rammelsberg[13] due to Mosander, and are as follows (p. 424):

These ratios do not indicate the presence of any magnetite and, of course, may not represent the composition of the particular sample here studied. They point, however, to a high content of Fe_2O_3 in ilmenite from Arendal.

Several specimens purchased a number of years ago from a dealer and labelled "Arendal, Norway" have been studied. In

[13] *Op. cit.*, p. 523.

	(*a*) Magnetic.		(*b*) Non-magnetic.	
	Per Cent.	Molc. Ratio.	Per Cent.	Molc. Ratio.
SnO_2	3.68	.024		
TiO_2	20.64	.258	24.25	.303
Cr_2O_3	—	—	.45	.006
Fe_2O_3	55.86	.355	60.16	.340
FeO	19.70	.267	14.29	.273
MgO	.74	.018	1.13	.028
	100.62		100.28	
Sp. gr.	4.745		4.848	

(*a*) $RO_2 : RO = .282 : 285$, $Fe_2O_3 = 56.7$ per cent. ilmenite (including SnO_2 with TiO_2) = 43.30 per cent.

(*b*) $RO_2 : RO = .302 : 301$, $Fe_2O_3 = 60.16$ per cent. ilmenite = 39.84 per cent.

color, streak, character of fracture and magnetism, these resemble very closely the Miask ilmenite. The polished surface shows them to consist of irregular grains distinctly though faintly demarked from one another by boundaries and by slight variations in tint. There is some gangue present about and within the grains, and a small amount of material in the form of very minute irregular patches, or groups of small patches, having a bright white color. These suggest hematite or rutile in color. Otherwise the ilmenite is homogeneous. They differ in appearance and properties sharply from ilmenite just described and known to come from Arendal.

Kragerö, Norway.—The specimen used for study was a large (4 mm. by 1½ cm.) roughly faceted crystal of the habit characteristic of this locality. It unfortunately shows obvious signs of alteration; the surface is a reddish brown and shows a platy structure suggestive of hematite plates and the reddish-brown alteration extends through the body of the crystal. Some calcite and quartz also penetrate the crystal. The black, fresh-looking parts give a red streak and are not magnetic. A polished surface shows that the body of the crystals, aside from some gangue and earthy spots, is not homogeneous although this is possibly also due to alteration. The greater part is of a pale reddish color rather deeper than that of ilmenite. This is broken up most ir-

regularly by a much lighter material which is undoubtedly hematite.

There is considerable variation in the analyses of ilmenite from this locality and in view of the alteration apparent in the specimen studied it appears useless to consider its composition further.

Ilmenite from Snarum, Norway.—The material studied consisted of several tabular crystals about 1 cm. in diameter by ½ cm. thick. These were embedded in a matrix of serpentine and their surfaces are more or less rounded. They are black, lustrous, slightly magnetic and have a reddish-brown streak, distinctly like hematite. Polished basal sections appear homogeneous with low magnifications, but, using a $\frac{1}{12}$ oil immersion objective, rather numerous narrow bands appear and these, as a rule, run parallel to a well-defined set of triangular parting lines, parallel to the rhombohedral edges. In reflected light the color of the matrix is nearly white to yellowish white though probably darker than pure hematite. The lamellæ appear slightly darker by contrast.

Two analyses of this mineral from Snarum are given below:

	Rammelsberg.[14]	Molc. Ratio.	Doby & Melzer.[15]
TiO_2	10.02	.125	5.64
Fe_2O_3	77.17	.485	95.56
Al_2O_3[14]	1.48	.014	
FeO	8.52	.118	.11
MgO[14]	1.33	.033	1.10
	98.50		100.38
Sp. gr.	4.943		5.041

Doby and Melzer found 93.62 per cent. Fe_2O_3 after oxidizing the powdered mineral at a high temperature in oxygen, thus indicating very little ferrous oxide. The analysis shows clearly that this mineral is substantially a hematite as is indicated by its streak and the color of its polished surface. What the lamellæ are is uncertain. If Rammelsberg's figures are correct they suggest that the lamellæ may be ilmenite. They may, however, be

[14] *Op. cit.*, p. 526.
These belong in part to Völknerite.
[15] *Op. cit.*, p. 540.

magnetite. If so, it would account for the magnetic properties although these may conceivably result from other causes. So far as chemical composition is concerned this mineral is very near hematite. Its crystal symmetry appears, however, to place it with the ilmenites.

Washingtonite, Litchfield, Connecticut.—The specimen studied was a tabular crystal 1½ cm. in diameter by ½ cm. thick, showing besides the base, the forms of the prism and rhombohedron similar to Fig. 2, in Dana's "System of Mineralogy" and figured after Rammelsberg. A little quartz is attached to, and grown into, one side of the crystal. The crystal is somewhat magnetic, black in color, but gives a distinctly reddish-brown streak.

Examined with the microscope, the polished base, even under low magnifying powers, shows a non-homogeneous character. In a matrix that appears yellowish white are many spots of a distinctly darker and reddish-brown shade. These vary much in size, and are for the most part rounded and irregular in outline. They occur commonly in clusters. There is a slight suggestion of regularity in the arrangement of many of them. In addition there are a few narrow straight lines or bands of no great length present between, and running into, the reddish-brown spots. These are arranged according to a definite pattern, not infrequently branching one from another. They may possibly be magnetite instead of ilmenite; the identification is difficult on account of their narrowness. The appearance is shown in the photograph (Plate XXVII., *A*).

A polished prism face showed a series of elongated, relatively short, narrow lamellæ, of reddish-brown color, often tapering bluntly, which run approximately parallel to the base, and these are accompanied by a similar but much smaller and more numerous series parallel to and between the larger lamellæ. In addition to these, there is another series of straight narrow bands, much less numerous, which often branch at an angle. These correspond to the branching bands seen on the base, while the other lamellæ correspond to the spots referred to. The appearance is illustrated by Plate XXVII., *B*. It appears, therefore, that the intergrowth takes chiefly the form of thin tabular lamellæ

of ilmenite parallel to the base and, to a less extent, of stripes arranged parallel to other crystallographic directions. The lamellæ as seen on the prism resemble in form the hematite lamellæ seen in the ilmenite of St. Urbain and Egersund (see later), but here it is the ilmenite that forms the lamellæ, so we conclude that here is a case of an intergrowth of the two minerals in which hematite acts the host.

Analyses by Rammelsberg[16] give the chemical composition as follows:

	Per Cent.	Molc. Ratio.	Ilm.	Mag.	Hem.
TiO_2.....	23.72	.296	.296		
Fe_2O_3.....	53.71	.336		.031	.305
FeO.....	22.39	.312	.296		
MnO.....	.25	.003		.031	
MgO.....	.50	.012			
	100.57				
Sp. gr.....	4.986				

Sp. gr. 4.986.

Assuming the above simple compounds as present we have, approximately, ilmenite, 45 per cent.; hematite, 48.7 per cent.; magnetite, 7.1 per cent. Presumably the magnetite and hematite form a solid solution and while it was not possible to estimate the amount of ilmenite present as such, the appearance indicates that it is subordinate in amount to the hematite. As suggested above, the magnetite molecule may be represented in part, at least, by the series of straight lines intergrown in the hematite.

Warwick, N. Y.—Material from this locality has been analyzed by Rammelsberg[17] and by Penfield and Foote.[18]

The latter give the following analysis (I.) which is in general agreement with that of Rammelsberg made earlier.

In column II. is given for comparison an analysis of picroilmenite made by Crook and Jones.[19]

[16] *Op. cit.*, p. 521.
[17] *Op. cit.*
[18] *Am. Jour. Sci.* (4), Vol. 4, 1897, p. 108.
[19] *Min. Soc.*, London, 1906, 14, 165.

	I.			II.	
	Per Cent.	Molc. Ratio.		Per Cent.	Molc. Ratio.
TiO_2	57.29	.716	.716	57.64	.720
SiO_2	.37	.006	.006		
Fe_2O_3	1.87	.012	.012	10.17	.063
FeO	24.15	.336		16.57	.231
MnO.....	1.10	.015	.750		
MgO.....	15.97	.399		15.56	.386
	100.75				
Sp. gr.	4.345				

The ratios derived from I. suggest

$RO : TiO_2 = 716 : 716 = 1 : 1 + RO : R_2O_3 = .012 : 012 = 1 : 1$,

leaving a small residual of RO (=.012), silica (.006). The polished surface of a crystal from the same lot of material that was studied by Penfield and Foote showed a substantially homogeneous crystal. However, a few narrow straight bands of slightly different color from the matrix and even differing slightly one from another are present. These bands have a distinctly visible lining or fibration normal to their sides. They are probably magnetite and their amount is quite in keeping with the small per cent. (2.7 per cent.) of magnetite indicated by the analyses. The main part of the ilmenite is broken by faint irregular lines which divide the field into areas and suggest that the crystal has been subjected to some mechanical strain. The outside surface, it may be noted, is quite rounded, though it still preserves something of its original habit. It may well be that the magnetite is a later formation deposited along parting lines through the crystal.

The analysis of an ilmenite of very similar TiO_2 and MgO content given in II. shows a wide divergence in the Fe_2O_3 and FeO values from those in the Warwick mineral. There is apparently a large excess of TiO_2 over the ilmenite (RO; TiO_2) ratio, and the suspicion arises that there may be an error in the determination of the Fe_2O_3 and FeO. The total iron in the two analyses is very nearly the same. It may be noted that, on the whole, the highly magnesian varieties, the so-called "Geikelites" correspond rather closely to the $R^{II}TiO_3$ type formula as figured from some eight analyses listed in Hintze's Handbuch, p. 1886.

Such discrepancies as these are may well be due to small inaccuracies in the analyses.

Iron Mountain, Wyoming.—The titanic iron ore from this locality has been quite fully described by Singewald,[20] who gives several photographs of polished and etched sections. He notes considerable variations in the characters of the ore in regard to composition, granularity and in the minute details of its structure. The sample here studied was taken from a mass of several kilograms weight collected by Professor W. O. Crosby. Particulars as to its exact location are lacking. The ore consists of a medium to coarsely granular aggregate of grains, which are mainly a magnetite-ilmenite intergrowth, ilmenite, a considerable percentage of a dark-green spinel and a smaller amount of other silicate material. The spinel grains are often of the same magnitude as the ore grain, but the mineral also occurs as small grains within the magnetite grains and may also be the material which in the form of numerous inclusions lies commonly along the directions of the octahedral planes of the magnetite. These vary much in amount and take the form of straight lines or dashes of variable length. They often break up into a series of dots or dots and dashes or isolated dots may occur alone. Between the larger and stronger lines there are often finer and more numerous parallel ones. In the polished specimen the spinel appears as a dark gray, highly lustrous grain and the dashes and dots referred to present precisely the same appearance. As spinel is known to occur in such crystallographic relation with magnetite, it seems possible that such is their character. Their appearance is shown in Plate XXVIII., *A*.

The ilmenite grains are much less abundant than the magnetite-ilmenite grains, and as a rule take a more perfect polish. Their substance appears perfectly homogeneous, aside from occasional small inclusions.

The magnetite-ilmenite grains appear homogeneous even under high-power dry objective, except for the straight lines, dots or dashes above referred to. With a $\frac{1}{12}$ oil immersion objective, however, the grains are seen to consist of an extremely fine in-

[20] *Op. cit.*, pp. 122–125.

terpenetrating network of lamellæ, of slightly but clearly contrasted color, one set being slightly more reddish than the other. These minute lamellæ are arranged substantially parallel to the direction of the octahedral planes. They are always exceedingly minute, of somewhat varying width and usually taper out. Several intersecting sets are present. Etching with dilute HCl attacks one set of these lamellæ and brings out the structure, so that it can be seen with the highest dry objectives. The accompanying photograph (Plate XXVIII., *B*) will serve to illustrate the appearance of these intergrowths.

Singewald[21] states that the most abundant inclusions of ilmenite show as "dashes and dots." He says:

> "The dashes occur in some cases widely spaced . . . in other cases they are very closely crowded, giving a dense network effect. . . ."

Again he speaks of the dots as being of two sizes, the larger occurring irregularly and regularly along the outlines of the magnetite grains and along parallel cleavage directions. Minute dots occur in irregular swarms. He gives several photographs of these intergrowths. Judging by the appearance of these photographs and his descriptions, the dots and dashes correspond to what have been described above by the writer as included spinel or perhaps other non-metallic material. The magnification of Mr. Singewald's photographs ($\times 60$) would not show the real magnetite-ilmenite intergrowth in the specimens here studied. The dots and dashes which are prominent features of the writer's specimens are certainly not ilmenite, though strikingly like those figured by Singewald so far as can be judged by the photographs and descriptions. The material studied by Singewald was much more varied than that at the writer's disposal and there may be great variation in the size and character of the intergrowth in different specimens from this locality. The same remarks apply to the ore from Lake Sanford, New York, described later on, but the writer cannot escape the conviction that the real ilmenite-magnetite intergrowth is a much more minute and entirely different thing from that described as such by Singewald.

[21] *Op. cit.*, pp. 122–3, Plates XI., XII., and XIII.

Lake Sanford, New York.—The specimen examined was given to the writer some years ago by Dr. Newlands, of the New York State Geological Survey, who had studied the ore and locality.[22] He has shown this ore to be a granular aggregate of ilmenite and magnetite. Singewald has also described this ore microscopically.

The present specimen consists in the main of strongly magnetic grains with a considerably smaller proportion of ilmenite. The mean diameter of the grain is probably somewhat under 5 mm. and the amount of ilmenite will probably not exceed 20 per cent. of that of the magnetite. Considerable gangue is present and this consists of plagioclase, biotite and augite. A green spinel occurs in the form of small irregular grains in the ore. Along the boundaries of the ore grains there often occurs a narrow band of transparent finely crystalline material whose exact character has not been investigated.

With lower magnifications the highly polished surface shows only a slight contrast in color between the ilmenite and magnetite grains, the latter may be easily recognized by the presence of very narrow straight bands following the directions of the octahedral parting. With higher powers a series of minute dark rods and specks may be seen lying between the longer and more conspicuous bands, and having the same general trend. These are illustrated by plates XXIX and XXX. In color the bands, rods and specks are identical among themselves as they are with the larger spinel inclusions in the grains and all are obviously nonmetallic in character. With the $\frac{1}{12}$-in. oil-immersion objective the body of each grain is seen to consist of intergrown lamellæ of slightly different shades of pale reddish brown. On etching with dilute HCl the nature of the intergrowth is clearly brought out and appears as a very delicate, intricate intergrowth of exceedingly minute lamellæ of dull magnetite and bright ilmenite (Plate XXX *A* and *B*). The general arrangement of this intergrowth is parallel to the octahedral planes of the magnetite. The lamellæ vary in width and length, and apparently somewhat in relative amount from point to point, although this is probably more apparent than real.

[22] N. Y. State Educational Department Bull. 23.

Regarding the coarser lamellæ, etc., it may be further said that when examined with high powers (after etching) they are seen to consist of a line of material of grayish color on either side of which is often a more or less continuous band of ilmenite or magnetite. Whatever the exact nature (it may be spinel) of the material forming the bands, it is non-metallic in character and has associated with it silicate material and also here and there a little pyrite. The presence of the latter at once suggests secondary deposition and it may be that all of the material forming these lamellæ are due to such a cause. The minute, rounded or oval spots earlier referred to are often seen accompanying the larger lamellæ. Plate XXX., *A* and *B*, are photographs of an etched specimen and will serve to illustrate the structure just described.

In the material examined from this locality, as with that from Iron Mountain, Wyoming, and indeed in the case of the Cumberlandite also (see beyond), there is an exceedingly fine intergrowth of magnetite and ilmenite through which runs, with a generally definite pattern, lamellæ, etc., of a distinctly different and non-metallic character. This latter material appears, so far as the writer is able to judge, to be identical with what Singewald has described as ilmenite lamellæ, etc., intergrown in the magnetite.

Cumberlandite, Cumberland, R. I.—This rock has been previously described by the writer.[23] The original study of the polished rock was made with the aid of a rather poor reflecting device, so it has seemed desirable to reinforce the original description of the metallic portion of the rock by using the much better instrument now available.

The ilmenite-magnetite part of the rock forms a mesh-like matrix enclosing olivine crystals and less commonly labradorite. Some spinel occurs in the ore matrix.

The ore is substantially of uniform character throughout. With lower powers the polished surface shows clearly a series (Plate XXXI., *A*) of lines following the octahedral planes, these consist of non-metallic material which may be secondary. With

[23] *Am. Jour. Sci.* (4), Vol. 25, 1908.

high magnification two sets of metallic lamellæ may be seen, one (ilmenite) slightly more reddish in color than the other (magnetite). Their arrangement is probably parallel to the octahedral planes.[24] On etching for a few minutes with dilute HCl, the recticulate intergrowth is very clearly and beautifully brought out. The ilmenite retains its surface, the magnetite becoming dull. Plate XXXI., *B*, shows the appearance of this. It should be noted that the magnetite-ilmenite intergrowth in this specimen is coarser textured though otherwise entirely similar to that in the Iron Mountain and Lake Sanford ores, but it is still much finer than anything figured by Singewald.

St. Urbain, Quebec.—The ilmenite from this locality has already been described by the author,[25] but as it illustrates a distinct type of intergrowth a description of it will be included here.

The material consists essentially of a medium-grained aggregate of ilmenite crystals. In the purest phase not over 5 per cent. of gangue is present and this consists of spinel, plagioclase (altered), a little biotite and hornblende (after pyroxene). One phase of the rock, however, contains as much as 20 per cent. of rutile with sapphirine, spinel, plagioclase, etc. Throughout, the character of the ilmenite is identical. Its grains are not attracted by the ordinary magnet; its streak is a dark reddish or brownish black. The polished surface shows that the texture is xenomorphic. The individual grains consist of ilmenite, of a pale reddish-brown color as seen with the reflecting microscope, in which is about 20 per cent. of hematite. The latter forms a series of narrow lamellæ substantially parallel in arrangement for a given grain. Along their length minor fluctuations of width and orientation are present and there is a general tendency to abrupt tapering at the ends. Not infrequently several adjacent lamellæ will curve away, one after another from the general direction. Their length varies, but is always many times the

[24] The writer originally thought of this intergrowth as following the directions of the rhombohedral planes of ilmenite. It now seems quite certain that it is the magnetite that controls the orientation. It is probably true that the ilmenite lies with its basal planes parallel to the octahedral planes of the magnetite.

[25] *Am. Jour. Sci.* (4), Vol. 33, March, 1912.

width. They are occasionally cut across and slightly displaced by minute fault lines doubtless produced by movements in the rock mass as a whole. Between the larger lamellæ a parallel series of similar but still more minute lamellæ may be seen. These appear to be most abundant midway between any two of the larger lamellæ. Their appearance, illustrated by Plate XXXII., *A*, resembles strongly the microperthitic texture in feldspar.

The chemical composition of this intergrowth as calculated from the analysis[26] of the rock as a whole is as follows:

	Per Cent.
TiO_2	43.4
Fe_2O_3	19.3
FeO	34.7
MnO	.4
MgO	2.2
	100.0

The percentage of Fe_2O_3, or hematite, agrees well with a micrometric estimate made on the polished specimen which gave 20 per cent.

In passing, it may be noted that Singewald[27] has described and figured an exactly similar intergrowth from the river Chaloupe, Canada. He recognized that it differed from the other ilmenite intergrowths, saying that it did not etch as readily and suggesting that it might be a magnetite-ilmenite eutectic.

Egersund, Norway.—The specimen studied came from the collection of the late Mr. Richard Pearse, of Roxbury, Mass., and was purchased by him in the early sixties from a mineral dealer in Freiberg, Saxony. This material bears a striking resemblance to the St. Urbain ilmenite, except that when broken up, a certain proportion of the small fragments are readily attracted by the magnet.

A thin section shows the presence of some spinel grain and occasional crystals of apatite, also a little silicate material. The polished surface shows the same intergrowth of hematite lamellæ

[26] *Op. cit.*, p. 275.
[27] *Op. cit.*, p. 24 (Plate XVI., 13).

in ilmenite as did the St. Urbain rock. A rough quantitative estimate places the amount of hematite at 15 per cent. The lamellæ are much ($\frac{1}{10}$ ca.) narrower, however, as can be seen by comparing Plates XXXII., *A*, and XXXII., *B*.

Otherwise the general appearance and characteristics of this intergrowth are like that of a St. Urbain rock. Plate XXXII., *B*, shows a typical area. Here and there, among the grains, are irregular patches of material of quite different structure and with these patches there is often some gangue. The metallic portions consist of what appears to be ilmenite with irregular outline, but without hematite, and with it is associated magnetite of slightly lighter color. This accounts for the magnetic properties of a portion of the fragments above alluded to.

Several analyses of this ilmenite are given in the literature by Rose, Mosander, Kobell, Rammelsberg and Tamm. Rammelsberg[28] quotes and discusses the earlier analyses and gives one by himself. He also gives a later analysis.[29] All of these appear to have been carried out on the massive granular ore, occurring as dike-like masses or as schlieren in norites or anorthosite rocks.

	No. 1.		No. 2.		No. 3.	
	Per Cent.	Molc. Ratio.	Per Cent.	Molc. Ratio.	Per Cent.	Molc. Ratio.
TiO_2	51.30	.640	45.77	.571	41.96	.524
SrO_2					.60	
Fe_2O_3	8.87	.056	14.10	.088	22.22	.139
FeO	39.83	.555	39.50	.550	31.16	.434
MnO					.28	.004
MgO	.40	.010	1.14	.028	3.16	.079
CaO					.55	
P_2O_5					.02	
	100.40		100.52		99.95	
Sp. gr.	4.744		4.791			

In considering these analyses and the ratios derived from them it must be borne in mind that a certain amount of spinel is present and some magnetite. How much is not known, so that any exact computations cannot be carried out. Assuming that

[28] *Op. cit.*, p. 516.

[29] *Mineral. Chem.*, 1875.

the titanium present as TiO_2 is combined with RO in ratio of 1 : 1 we may set down the following:

	I.	II.	III.
TiO_2	.565	.571	.517
RO	.565	.571	.517
Excess TiO_2	.075 or 6.0%	—	.097 or 0.56%
Fe_2O_3	8.87%	14.10%	22.22%
Excess RO		.007	

The excess of TiO_2 in I. is noticeable. It may be due to an error in the analyses. They all agree in showing an excess of Fe_2O_3, which appears from the microscopic study to be largely present as intergrown hematite.

Iserine, Iserweise, Bohemia.—A small lot of the so-called "iserine" from the original locality was studied. This consisted of small black rounded grains ranging from 5 mm. to 10 mm. in diameter. Some of these are strongly magnetic, others are not effected by the magnet. In polishing one of the non-magnetic grains, it was discovered that it was strongly magnetic afterward, and this result was obtained with several other grains. Polished and etched surfaces appear perfectly homogeneous.

A study of the literature of iserine shows a great variation in chemical composition and a corresponding variation in density. The magnetic properties also vary.

A study of the molecular ratios derived from the best analyses made by Rammelsberg[30] yield the following figures:

	H. 17.	H. 16.	H. 18.	H. 15.
TiO_2	.714	.527	.520	.468
Fe_2O_3	.098	.146	.181	.178
FeO	.362	.425	.334	.407
MnO		.025	.014	.040
MgO	.043	.039	.110	.074
		or		
TiO_2	.714	.527	.520	.468
RO	.405	.489	.469	.521
Excess TiO_2	.309	.038	.051	.053
Fe_2O_3	.098	.146	.181	.178

[30] *Op. cit.*, pp. 520 and 532; Hintze, "Handbuch der Mineralogie," Nos. 15, 16, 17, 18.

In not one of these analyses is the ratio $RO:TiO_2$ even approximately equal, and in the No. 17 the excess of TiO_2 is very large. This led Rammelsberg to consider that in this ilmenite there were present titanates of both ferrous and ferric iron. From the known occurrence of free rutile in material of this type (see beyond) it is not improbable that the large excess of TiO_2 shown in some cases may be due to the presence of rutile. The large excess of Fe_2O_3 in all is notable.

Rutile-Ilmenite Pebbles.—In looking over some round black pebbles from placer concentrate from the Pacific coast, exact locality unknown, besides some magnetite, the greater part appeared to be ilmenite. A few, however, of the pebbles were found to be in part rutile. Two of these were polished and showed in one case a well-developed reticulate intergrowth of rutile and ilmenite, in the other what appeared to be a partial replacement of rutile by ilmenite; the outside of the pebble being almost entirely ilmenite. Such material might easily be mistaken for ilmenite and this possibly accounts for the very high TiO_2 relative to the iron oxides shown by some analyses of ilmenite, notably some of the iserines.

Magnetite, Magnet Cove, Arkansas.—This has been described and analyzed by Harrington.[31] The analysis is as follows:

	Per Cent.	Molc. Ratio.	
TiO_2	2.40	.030	.030
Fe_2O_3	59.01	.369	.470
Al_2O_3	10.37	.101	
FeO	16.82	.234	.500
MnO	2.10	.029	
MgO	9.47	.237	
	100.17		
Sp. gr.	4.558		

Sp. gr. 4.558.

This corresponds exactly to $RO:R_2O_3 = 470:470 = 1:1$ $+ RO:TiO_2 = .030:030 = 1:1$, and is a magnetite grading toward spinel. The ilmenite molecule is probably held in solid solution. We might consider the titanium as Ti_2O_3 and the min-

[31] *Mineral. Mag.*, 14, 1907.

eral, a solid solution of magnetite and R_2O_3 where R_2 is Ti and Fe. Under the microscope a polished surface is perfectly homogeneous.

Ilmenite from Chester Hill, Mass.—The ilmenite in this specimen consists of a number of thin plates (1–3 mm. thick) embedded in albite feldspar. The parting lines are strongly developed. The color and streak are intensely black.

Polished surfaces show the material to be quite homogeneous except for an occasional narrow band of lighter color, probably hematite.

A similar homogeneous structure has been noted in a tabular ilmenite crystal with rounded edges (1 cm. diam., 5 mm. thick) from the granite pegmatite veins cutting the granite in the quarries at Rollstone Hill, Fitchburg, Mass.

A thinly tabular hematite, reacting, however, for titanium, from a quartz vein, locality given as Madoc, Ontario, was polished and examined. Clearly defined bands of hematite were seen grown in parallel position with the ilmenite. Another sample of similar habit, but having a red streak, seemed to be entirely hematite.

General Considerations and Conclusions.—There appear to be several fairly well defined types among the minerals which go under the name of "titanic iron ores." One type is of homogeneous structure and, together with the gieklikites, appears to belong crystallographically to the same class and to be very similar in habit. The Miask ilmenite may perhaps be chosen as best representing the iron-rich members of this type. The analyses of this mineral, so far as they can now be interpreted, indicate the predominance of the molecule $Fe^{II}TiO_3$ with a notable percentage of Fe_2O_3, presumably in solid solution. The magnesian varieties show, as a rule, but little Fe_2O_3. The minerals from Snarum and Arendal apparently run 93 per cent. to 55–60 per cent., respectively, of Fe_2O_3, and these seem to form a continuous series with the Miask type, if we may judge by the gradations in axial ratios as given by Doby and Melzer.[32] Hence it

[32] *Zeit. f. Kristal.*, 39, 1904, p. 540.

may be inferred that there is at least a wide range of miscibility existing between the molecules $R^{II}TiO_3$ and Fe_2O_3, if they are the molecules really present.

We have to include here also the homogeneous ilmenite grains which occur with the magnetite-ilmenite intergrowths in the ore from Iron Mountain, Wyoming, and from Lake Sanford, New York, and elsewhere.

Another well-defined type is that of the St. Urbain, Quebec, and Egersund, Norway, ilmenites. These consist of a very well-defined crystallographic intergrowth of ilmenite and hematite. If the chemical composition of these ilmenites may be compared with that from the Miask locality as shown in the accompanying analyses we note a strong similarity, and no significant differences

	Miask.	Egersund.		St. Urbain.
		(2).	(3).	
TiO_2	45.93	45.77	41.96	43.4
Fe_2O_3	14.30	14.10	22.22	19.3
FeO	36.52	39.50	31.16	34.7
MnO	2.72		.28	.4
MgO	.59	1.14	3.16	2.2
			1.17	
	100.06	100.52	99.95	100.00

appear to explain the striking contrast in structures revealed by the microscope. The same may be said if we compare the chemical compositions of the iserine with that of the St. Urbain ore. Why this difference?

The chemical data, though they may be uncertain, particularly with regard to the ferrous and ferric iron values, are equally likely to be in error in the case of one type as in the other, and can hardly as yet be used effectively. The writer is inclined to the opinion that we have here to deal with a case of readjustment in the equilibrium relations of two compounds. In the Miask type we have apparently solid solution. In the St. Urbain type two phases appear, and it seems probable that in the latter case we see the results of an unmixing of an originally homogeneous solid solution. Both the Egersund and St. Urbain rocks occur

as dikes in anorthosite in regions that have passed through a profound metamorphic history. The thermodynamic environment that has surrounded these rocks has unquestionably changed profoundly since their original crystallization, and we may easily believe that the two molecules involved are not miscible under the conditions that have been imposed upon them since their original formation. The other type, Miask, etc., has not passed through a similar history and has remained unchanged.

In the case of the Washingtonite and the ilmenite from Kragerö, we have a somewhat similar intergrowth but with the hematite as host and the ilmenite contained as lamellæ. The same explanation may apply, however, to these.

The straight bands of magnetite noted in the Warwick, New York, ilmenite and in that from Snarum and Arendal may be later secondary crystallizations along the directions of the parting planes.

Still another type is that illustrated by the magnetite-ilmenite intergrowths such as are found in the Cumberlandite, Rhode Island, and in the ore from Iron Mountain, Wyoming, and Lake Sanford, New York, ore. Though these intergrowths differ somewhat in detail, their similarity is so strong as to naturally group them together. It is clear from a study of the chemical analyses of these ores[33] that the ferrous oxide percentage is, as we would expect, relatively high, thus explaining readily the presence of the magnetite molecule. It appears that here we have, leaving out incidental silicate gangue, retained doubtless from the rock magmas from which the ores crystallized, granular aggregates of ilmenite, distinct homogeneous grains, spinel, also as distinct grains, and a residual granular mass, the individuals of which consist of a magnetite-ilmenite intergrowth. This suggests a eutectic relationship as a reasonable supposition. The strongly marked lamellæ parallel to the octahedral planes may, as has been suggested, be seondary silicate material of later origin. If it be true that the dashes and dots and straight intersecting lamellæ described by Singewald are, as he claims, ilme-

[33] A collection of these may be found in the paper by Singewald frequently referred to.

nite, then we must conclude that the character of the ilmenite intergrowth varies widely in different specimens from the same locality.

In magnetites such as that described by Harrington from Magnet Cove, Arkansas, and doubtless others low in titanium, the ilmenite molecule or the titanium oxide present is probably in solid solution in the magnetite, just as may be the case with Fe_2O_3 and Fe_3O_4.[34]

We have also the puzzling fact that there are ilmenites like that from Snarum, Norway, with low titanium (5 to 10 per cent. TiO_2) which appear crystallographically to be of the ilmenite type, though essentially hematites in composition. These contain intergrown lamellæ, which may be ilmenite and thus account for the titanium content, though this seems doubtful, particularly as the lamellæ may be magnetite. There are also hematites, so-called, notably the "Eisenrose" from St. Gottard, whose analyses show as high as 12 per cent. of TiO_2 though usually less. Microscopic study of these might show lamellar intergrowths of hematite and ilmenite or even rutile which would explain the titanium content. Still it is noted that some of the specimens of the "Eisenrose" are stated to have a black or nearly black streak which would suggest that they are really of the ilmenite type. Furthermore, it is known that artificial Ti_2O_3 is crystallographically like hematite and the question arises as to whether or not the rhombohedral Ti_2O_3 may not be in solid solution (isomorphous) with Fe_2O_3 in certain of these titaniferous hematites as claimed by Groth, while in those like the Snarum ilmenite we have a dimorphous modification of the rhombohedral tetrahedral class.

While it is clear that a definite settlement of the relations of the titanium-iron oxides must await experimental study, it seems probable that such study would show that there exists a limited solid solution of the ilmenite and magnetite molecules with a eutectic and that between ilmenite and hematite there is a complication of complete solid solution at higher temperatures with an inversion interval and limited miscibility at lower temper-

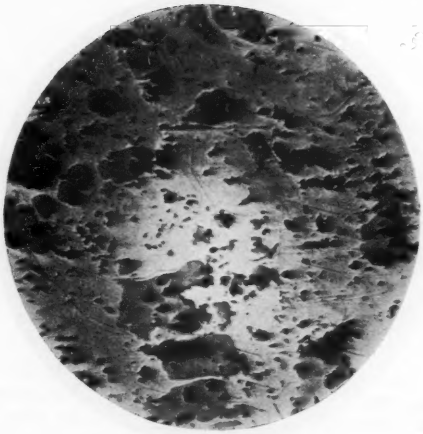
[34] Sosman & Hostetter, *Jour. Am. Chem. Soc.*, Vol. 38, No. 4, Apr., 1916.

atures. That Ti_2O_3 or TiO_2, as such, may enter into solid solution is not improbable, for while the excess TiO_2 shown by so many analyses of titanic-irons may be, and probably is, in part due to the presence of free rutile, there are cases where there is no evidence of rutile and yet an excess of TiO_2 is apparently present either as an oxide of titanium or possibly as some iron-titanium compound with a higher titanium ratio than is found in $R^{II}TiO_3$.

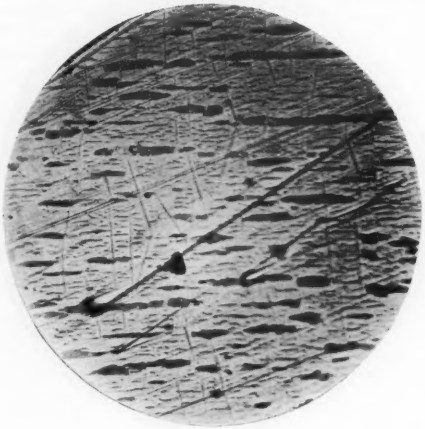
EXPLANATION TO PLATE XXVII.

FIG. A. Polished Basal Plane of Washingtonite Crystal, Litchfield, Conn. The dark patches are ilmenite; groundmass, hematite. A few faintly marked lines of another series of lamellæ may be seen. Magnification, 240.

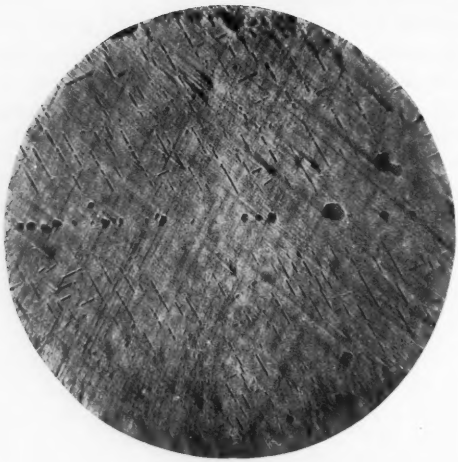
FIG. B. Polished Prism Face of Washingtonite, Litchfield, Conn. Darker lamellæ are ilmenite arranged parallel to base, smaller ones between these. The few straight lines are another set following other directions. These may be magnetite. Surface is somewhat scratched. Magnification, 240.



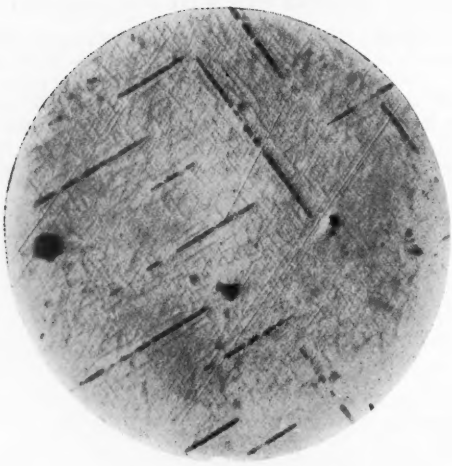
A.



B.



A.



B.

EXPLANATION TO PLATE XXVIII.

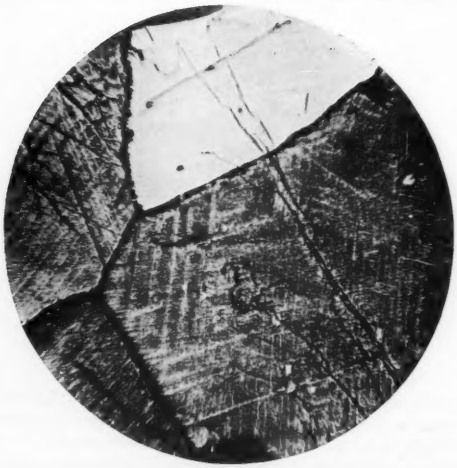
FIG. A. Titanic-Iron Ore. Iron Mt., Wyoming. Delicate series of straight lamellæ somewhat broken into, also line dots, of larger spots, some angular, in a crystal made up of a megnetite-ilmenite intergrowth. The latter is wholly invisible at this magnification. The spots and lines are spinel, or silicate material. The broader marks that cross the figure in two directions, are scratches not removed by polishing. Magnification, 91.

FIG. B. Titanic-Iron Ore. Iron Mt., Wyoming. The strongly marked (dark) lines and dashes or dots, as well as the separate dark spots are the same as those shown in Plate XXVIII., A. The matrix shows the fine interpenetrating lamellar intergrowth of magnetite and ilmenite. The extreme fineness of the intergrowth and slight contrast in color of the two minerals renders it difficult to bring out sharply in the photograph. Magnification, 518. Etched with dilute HCl.

EXPLANATION TO PLATE XXIX.

FIG. A. Titanic-Iron Ore, Lake Sanford, N. Y. The white grain is ilmenite, the dark are magnetite grains. The lines shown in the latter follow the parting planes of the mineral and are of transparent, probably silicate, material. Etched with dilute HCl. Note that the ilmenite is unattacked, and that along the boundaries is silicate material which shows block in the photograph. Magnification, 32.

FIG. B. Titanic-Iron Ore. Lake Sanford, N. Y. The two sets of black lines mark the octahedral parting planes of the magnetite, and consist of some transparent, probably silicate material. The intergrowth of magnetite-ilmenite is wholly invisible at this magnification. The specimen shows a set of minute scratches not removed by polishing. Magnification, 91.



A.

B.

A.

B.

EXPLANATION TO PLATE XXX.

FIG. A. Titanic-Iron Ore. Lake Sanford, N. Y. Below are two of the bands following the octahedral partings of the magnetite (the same seen in Plate XXIX., B); above the black crack is another of these bands showing oval enlargements, apparently of same character as the material of the bands. The groundmass shows the very fine magnetite-ilmenite intergrowth, the lighter colored markings being the ilmenite. Etched with dilute HCl. Magnification, 255.

FIG. B. Titanic-Iron Ore. Lake Sanford, N. Y. The two bands crossing the figure consist, centrally, of transparent, probably silicate material (the same as seen in Plate XXX., A) bordered here principally by magnetite. In the groundmass the lighter lines crossing in two directions are ilmenite lamellæ, the rest being magnetite. Etched with dilute HCl. The appearance of relief shown by the magnetite is here due to the fact that it is considerably tarnished. Magnification, 518.

EXPLANATION TO PLATE XXXI.

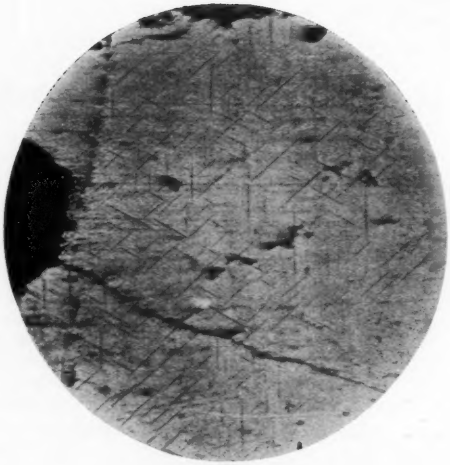
FIG. A. Magnetite-ilmenite, Cumberland, R. I. The narrow triangular markings crossing the magnetite-ilmenite grain consist of silicate material, or spinel, developed along the octahedral planes of the magnetite. The ilmenite and magnetite are not visible at this magnification. Unetched. Magnification, 91.

FIG. B. Intergrowth of magnetite (dark), and ilmenite (light), Cumberland, R. I. Etched with dilute HCl. Dark spot at the left is olivine. Magnification, 255.

EXPLANATION TO PLATE XXXII.

FIG. A. Hematite (light) in Ilmenite (dark), St. Urban, Quebec. This shows three differently orientated grains in contact. Magnification, 83.

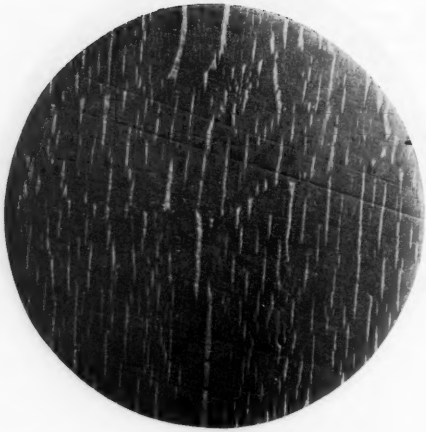
FIG. B. Intergrowth of hematite (light) in Ilmenite (dark), Egersund, Norway. Fine, faint series of lamellæ between the larger ones. The lamellæ are displaced along micro-fault lines. Magnification, 240.



A.

B.

A.



B.

INTRUSIVE ORIGIN OF THE GULF COAST SALT DOMES.[1]

G. SHERBURNE ROGERS.

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INTRODUCTION.

The origin of the great masses of salt that occur here and there beneath the Coastal Plain of Louisiana and Texas has been a favorite subject for speculation among geologists, especially in the last twenty years. Although some of the Louisiana domes have been known for a long time, the problem of their origin excited little general interest until 1901, when through the spec-

[1] Published by permission of the Director, United States Geological Survey.

tacular discovery of oil on Spindletop the domes acquired a vastly greater economic significance and attracted wide attention. Since 1863, however, their origin has been considered by a number of geologists; and because of the obscure nature of the problem and the lack of positive evidence a remarkable diversity of opinion has developed.

The drilling of several thousand wildcat wells on the Gulf Coast in the past twenty years has revealed several dozen new salt domes, and has given a fair knowledge of the shape and structural relations of their upper part. Of the lower portion,

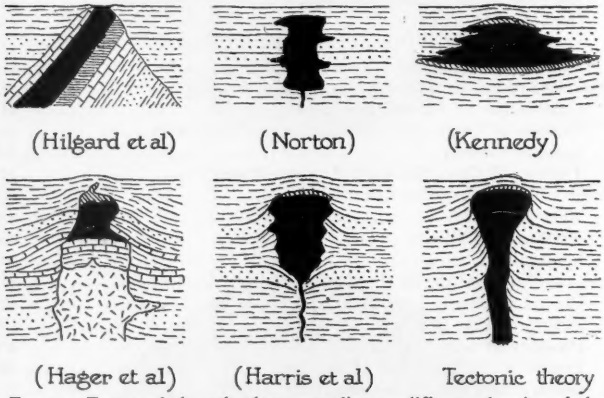


FIG. 54. Forms of the salt plugs according to different theories of their origin. (Only the upper portions of the plugs have been actually explored.)

however, we know nothing, and our conception of the form of the salt mass as a whole must rest entirely upon our theory of its origin. Figure 54, which shows the forms which the salt mass may be expected to have, according to some of the different theories, indicates the diversity of existing conceptions. As the form of the salt mass has a bearing on the possible existence of oil deeper than any yet found, its origin is of economic as well as scientific interest.

Nearly all of the theories that have been advanced to explain the American salt domes postulate precipitation of the salt from

ascending solutions, either during the deposition of the surrounding sediments or afterwards. Similar theories were formerly held to account for the salt domes of northwestern Europe and Roumania, but apparently these have all been discarded in favor of a group of tectonic theories, which emphasize the plasticity of salt and explain the domes as offshoots, caused by pressure, from a bedded salt deposit below. The writer, in the course of an examination of the Texas and Louisiana salt domes for the United States Geological Survey, recently observed evidence which seems to support a tectonic theory, and the purpose of this paper is to discuss the applicability of such a theory to the American domes. However, in view of our still insufficient knowledge, the selection of the most adequate hypothesis must be made partly through a process of elimination, and it will therefore be desirable to review critically the earlier theories as well.

The writer takes pleasure in acknowledging his indebtedness, for suggestions and advice, to Messrs. N. H. Darton, Sidney Paige, and other members of the United States Geological Survey.

CHARACTERISTICS OF THE SALT DOMES.

The relations of the Gulf Coast salt domes and the structure of at least their upper portions have been adequately described by a number of writers,[2] but a brief résumé at this point will prove convenient.

[2] Veatch, A. C., "Preliminary Report on the Geology of Louisiana," Louisiana Geol. Survey Rept. for 1899; also "The Salines of Northern Louisiana," Louisiana Geol. Survey Rept. for 1902.

Hayes, C. W., and Kennedy, Wm., "Oil Fields of the Texas-Louisiana Gulf Coastal Plain," U. S. Geol. Survey Bull. 212, 1903.

Hager, Lee, "Mounds of the Southern Oil Feld," *Eng. and Min. Jour.*, pp. 137 and 180, July 28, 1904.

Fenneman, N. M., "Oil Fields of the Texas-Louisiana Gulf Coastal Plain," U. S. Geol. Survey Bull. 282, 1906.

Harris, G. D., "Rock Salt in Louisiana," Louisiana Geol. Survey Bull. 7, 1908; also "Oil and Gas in Louisiana," U. S. Geol. Survey Bull. 429, 1910.

Hopkins, O. B., "The Palestine Salt Dome, Anderson County, Texas," U. S. Geol. Survey Bull. 661-G, 1917.

Deussen, Alex., "The Humble Oil Feld, Texas," Southwestern Assoc. Petroleum Geologists Bull. 1, p. 60, 1917.

Distribution and General Relations.—The salt domes occur at intervals throughout a belt extending from north-central Louisiana at least as far southwest as the Rio Grande in southern Texas. Unconsolidated Tertiary and Quaternary sediments constitute the surface formations throughout this belt, except in very small areas around some of the north Louisiana and Texas domes, where Cretaceous rocks crop out. In the northern area the structural disturbance is thus visible at the surface, but the only indication of domes nearer the coast are topographic irregularities. A few of these domes form mounds rising 50 to 125 feet above the surrounding plain; others form mounds only a few feet high or are marked by sunken areas or small lakes, and many occur beneath country that is almost perfectly flat. Some of the domes near the Rio Grande are said to be marked by small outcrops of chalcedony, but on most of the mounds there are no rock outcrops. Springs of salt, acid, or sulphur water, and seeps of marsh and sulphur gas are, however, fairly common.

In ground plan most of the mounds are subcircular, their diameter ranging between 1,000 feet and 2 miles. A few of the mounds, however, are so elongated as to be true ridges, and the salt masses in several domes have been proved by drilling to be distinctly elliptical in form, the longer axis being three or four times as great as the shorter. The long axis of such domes commonly strikes about northeast.

The occurrence of the famous Five Salt Islands along a line trending about southeast was recognized by the earliest observers; and Veatch in 1902 pointed out that the north Louisiana domes occur along fairly distinct lines trending about northeast or parallel to the great Balcones fault of Texas. It is notable that the large number of new domes discovered since that time also fall along two intersecting series of roughly parallel lines. The alignment, though of course not perfect, is too striking to be ignored and is generally recognized as indicating the common relation of the domes to the main structural features of the region.

Dome-forming Material.—The core of the domes is composed of hard granular rock salt. The salt mass is generally more or less flat-topped and its flanks dip at angles of 30° to 80°. At

Avery Island the salt originally was within 15 feet of the surface and in several neighboring domes it was within 150 feet of the surface. In many other domes it is within 500 feet of the surface, though at Spindletop, Humble, and most of the other oil-producing domes, the top of the salt is not less than 1,000 feet deep, and in some oil fields which are supposed to represent domes no salt has been found to a depth of 3,000 feet or more.

The lower limit of the salt is not known. Certain wells in one or two domes are supposed to have passed out of the salt body into anhydrite, but as comparatively thin layers of anhydrite were found in the salt at higher levels it is very doubtful whether the bottom of the main mass was really reached. On the other hand a well at Humble penetrated pure salt to a depth of 5,410 feet and the salt in other domes is known to extend below 2,000 or 3,000 feet. It is practically certain that the vertical dimension of the salt mass is at least as great as the lateral dimensions, and it is entirely possible that it is many times greater.

In most of the domes the flat top of the salt mass is overlain by a cap rock composed chiefly of anhydrite, gypsum, limestone, and dolomite. The relative position of these materials is not constant, but in general the gypsum and anhydrite, when present, occur directly above the salt and are overlain by the limestone and dolomite. Limestone or calcareous sandstone also occurs as lenses in the sediments above the true cap. Sulphur is found at least in small quantity in the cap rock of nearly every dome, and in the caps of two or three there are large workable deposits. The sulphur occurs as irregular masses and veins, chiefly in gypsum or anhydrite but less commonly in limestone; it appears to have been deposited distinctly later than the rocks with which it is associated. Pyrite is common and generally abundant and chalcopyrite, galena, and sphalerite have occasionally been found in small quantity. The cap rocks of a few domes are 300 feet or more thick, but several have no cap rock at all, the salt being directly overlain by the sediments. In these domes the surface of the salt is likely to be irregular; in some it grades up into the sediments, and in others lenses of salt are intercalated in the sediments above the main salt mass.

Structure.—The intrusion or formation of the salt plug has produced a sharp local doming or quaquaversal structure, often accompanied by faulting, in the normally flat-lying sediments. In the Palestine, Tex., dome and in some of the north Louisiana salines, where Cretaceous rocks have been upthrust, the structure is strikingly shown at the surface. Veatch[3] compares the structure to a "sharp-pointed little dome such as might be formed in a sheet of dough by pushing upward with a blunt pencil"; Hopkins,[4] in describing the Palestine dome, states that "the results observed are analogous to those produced by driving a punch into a sheet of cold steel"; and both writers note the similarity of the structure to that caused by the intrusion of an igneous plug.

In the coastal domes, buried under Quaternary deposits, the structure is less obvious and it must be worked out by the correlation of well logs, but there is every reason to regard it as the same. The loose sands and gumbos above the top of the dome are only very gently arched, but down on the flanks of the salt mass the beds are tilted at high angles. At Humble these beds dip from 30° to 45°; at Damon Mound they dip from 45° up to angles so steep that a peripheral fault is suggested. The structure of the beds on the flanks of the Humble dome may be worked out in considerable detail from well logs, and it appears that the Yegua formation, which here lies directly on the flanks of the salt mass, has been pushed up through the overlying Catahoula-Fayette sands.[5] In other words, the sand series which is 150 feet or more thick at the greatest depth penetrated is pinched out at the 2,700-foot level; the underlying Yegua, which is several hundred feet thick down on the flanks of the dome, decreases in thickness and finally pinches out near the 1,200-foot level, or near the edge of the cap rock. The salt plug thus seems to have pushed the Yegua up through the Catahoula-Fayette and finally to have pierced through the Yegua itself.

[3] Veatch, A. C., "Geology and Underground Water Resources of Northern Louisiana and Southern Arkansas," U. S. Geol. Survey Prof. Paper 46, p. 29, 1906.

[4] *Op. cit.*, p. 264.

[5] Deussen, Alex., *op. cit.*, p. 75.

The amount of uplift in the various domes is also indicated by paleontologic evidence. Hopkins estimates that the uplift at the Palestine dome is at least 3,000 feet and Harris has determined the uplift as several of the coastal domes to be 1,500 feet or so. In a well at Saratoga, Dumble[6] found Jackson fossils at a depth of about 1,000 feet, and the fact that wells drilled within 100 yards to a depth of 1,200 feet or more did not reach the Jackson indicates a sharp and very local upthrust of these beds.

Summary.—The foregoing résumé of salt-dome characteristics indicates that any theory as to their origin must consider at least four main features:

1. The source of the salt and the manner in which it attained its present position;
2. The sharp local upthrust of the sediments surrounding the salt core;
3. The source and relations of the gypsum, anhydrite, limestone, dolomite, and sulphur usually found above the salt;
4. The alignment of the domes and their relationship to the main structural features of the region.

To these problems might be added a fifth, viz., the origin and mode of accumulation of the oil associated with most of the domes. It is generally thought, however, that the oil migrated to its present position after the formation of the dome and that its accumulation is governed chiefly by the dome structure; this is therefore a distinct problem which need not be considered here.

OBJECTIONS TO EARLIER THEORIES.

Classification of Earlier Theories.

In attempting to devise a theory of the origin of a group of phenomena there is a natural tendency on the part of most observers to overemphasize the features which appeal to them most strongly and to neglect other features whose explanation is just as essential. Thus some writers have been especially impressed

[6] Dumble, E. T., "The Occurrence of Petroleum in Eastern Mexico as Contrasted with that in Texas and Louisiana," Am. Inst. Min. Eng. Bull. 104, p. 1632, 1915.

by the uplift around the domes, and their theories, though accounting for this feature, pay scant attention to the source of the salt and the manner in which it attained its present position. Other writers, dwelling on the origin of the salt, have ignored the structure and their theories therefore fail completely. Harris was apparently the first observer to take both features into account and his theory has therefore been the most widely accepted, but it has objections which the present writer considers fatal. Moreover, neither Harris nor any other writer has attempted to explain, except vaguely, the origin of the cap-rock material, though it is recognized that this is a problem subsidiary to, and in some measure distinct from, that of the origin of the dome as a whole. On the other hand all recent writers have agreed that the alignment of the domes is due to the presence of lines of weakness probably existent in the Mesozoic or Paleozoic rocks at great depth and extended up into the Cenozoic beds by stresses incident to the loading of the Mississippi embayment.

The following table is an attempt to classify the theories that have been proposed to account for the salt domes of the Gulf Coast. It is complete so far as the writer knows, except for certain views tentatively advanced before the essentials of dome structure were understood and later retracted by their authors. The theories grouped as IV B 2 and 3 were developed by European geologists to account for the European domes and their application to the American domes has as yet been only briefly suggested.[7]

Theories of the Origin of Gulf Coast Salt Domes.

I. *Original deposits* (in place and contemporaneous with or older than surrounding rocks).

[7] Hahn, F. F., "The Form of Salt Deposits," Econ. Geology, Vol. 7, p. 120, 1912.

van der Gracht, W. A. I. M. von Waterschoot, "The Salt Domes of Northwestern Europe," Southwestern Assoc. Petroleum Geologists Bull. 1, p. 92, 1917.

De Golyer, E. L., "The Theory of Volcanic Origin of Salt Domes," Am. Inst. Min. Eng. Bull. 137, p. 987, 1918.

A. Bedded deposits from the evaporation of sea water by volcanic heat.—Thomassy (1860–1863).[8]

B. Bedded deposits from the evaporaiton of sea water in shallow lagoons.—Owen (1865).[9]

C. Cretaceous monadnocks.—Hilgard (1869); Lerch (1893); Clendenin (1896).[10]

D. Thermal salt spring deposits.—Norton (1915).[11]

E. Bedded deposits in salt lakes.—Kennedy (1917).[12]

II. *Secondary deposits from ascending magmatic waters* (salt, etc., of igneous origin?).—Coste (1903).[13]

A. Uplift due to igneous plug.—Hager (1904); Veatch (1906).[14]

B. Uplift due to laccolith.—Lucas (1918).[15]

III. *Secondary deposits from ascending artesian waters* (salt,

[8] Thomassy, R., Géologie pratique de la Louisiane, Chap. 8, Paris, 1860; Supplément à la géologie pratique de la Louisiane, Ile Petit Anse: Soc. Geol. de France, Bull., 2d ser. 1863, Vol. 20, pp. 542–544.

[9] Owen, R., "Report on Quaternary Rock Salt Deposits in Louisiana," *St. Louis Acad. Sci. Trans.*, Vol. 2, p. 250, 1868.

[10] Hilgard, E. W., "On the Geology of Lower Louisiana and the Rock Salt Deposit of Petit Anse," *Am. Jour. Sci.*, 2d Ser., Vol. 47, p. 77, 1869; "On the Geology of Lower Louisiana and the Salt Deposits on Petit Anse Island," Smithsonian Contributions, Vol. 23, Separate as No. 248, 1881.

Lerch, Otto, "A Preliminary Report upon the Hills of Louisiana," Louisiana State Exper. Sta. Geology and Agr., Vol. 1, p. 27, Vol. 2, pp. 53–109, 1893.

Clendenin, W. W., "A Preliminary Report upon the Florida Parishes of East Louisiana and the Bluff, Prairie and Hill Lands of Southwest Louisiana," Louisiana State Exp. Sta. Geology and Agr., No. 3, pp. 236–240, 1896.

[11] Norton, Edward G., "Origin of Salt Domes," Am. Inst. Min. Eng. Bull. 97, pp. 93–102, January, 1915.

[12] Kennedy, William, "Coastal Salt Domes," Southwestern Assoc. Petroleum Geologists Bull. 1, p. 34, 1917.

[13] Coste, E., "Volcanic Origin of Natural Gas and Petroleum," *Canadian Min. Inst. Jour.*, Vol. 6, pp. 73–123, 1903.

[14] Hager, Lee, "The Mounds of the Southern Oil Fields," *Eng. and Min. Jour.*, pp. 137, 180, July 28, 1904.

Veatch, A. C., "Geology and Underground Water Resources of Northern Louisiana and Southern Arkansas," U. S. Geol. Survey Prof. Paper 46, p. 29, 1906.

[15] Lucas, A. F., "Possible Existence of Deep-seated Oil Deposits on the Gulf Coast," Am. Inst. Min. Eng. Bull. 139, p. 1119, Jul., 1918.

etc., derived by the leaching of underlying rocks).—Goesmann (1867).[16]

A. Uplift due to pressure of ascending artesian waters.—Hill (1902).[17]

B. Uplift due to force of growing crystals:

1. Deposition due to cooling.—Harris (1907).[18]
2. Salt precipitated by mass action of other chloride solutions of magmatic origin.—Washburne (1914).[19]
3. Deposition due to drying effect of expanding gas.—Mills and Wells (1917).[20]

C. Uplift due to concretionary growth.—Woodruff (unpublished).

IV. Intrusions (offshoots from bedded salt deposits below).

A. In molten condition, due to igneous activity.—Turrentine (1913).[21]

B. In semi-plastic condition, due to excessive pressure on salt deposit below.

1. Pressure caused by igneous intrusion at great depth.
2. Pressure isostatic, due to weight of overlying sediments.
3. Pressure due to lateral or compressive thrust.

[16] Goesmann, C. A., and Buck, C. E., "On the Rock Salt Deposit of Petit Anse, Louisiana Rock Salt Co.," Rept. of the Am. Bureau of Mines, New York, 1867.

[17] Hill, R. T., "The Beaumont Oil Field," *Jour. Franklin Inst.*, Vol. 154, p. 263, 1902.

[18] Harris, G. D., "Rock Salt in Louisiana," Louisiana Geol. Survey Bull. 7, p. 76, 1907; "The Geological Occurrence of Rock Salt in Louisiana and East Texas," ECON. GEOLOGY, Vol. 4, pp. 21–23, 1909.

[19] Washburne, C. W., "Chlorides in Oil Field Waters," *Am. Inst. Min. Eng. Trans.*, No. 48, pp. 687–694, 1915.

[20] Mills, R. V. A., and Wells, R. C., "The Evaporation of Water at Depth by Natural Gases," abstract *Washington Acad. Sci. Jour.*, Vol. 7, No. 10, p. 309, 1917. (The theory is given in much greater detail in a manuscript which will shortly be published by the U. S. Geological Survey.)

[21] Turrentine, J. W., "The Occurrence of Potassium Salts in the Salines of the United States," Bur. Soils Bull. 94, p. 43, 1913.

Theories of Original or Contemporaneous Deposition.

Before the characteristic shape and depth of the salt masses were known several writers naturally regarded them as bedded deposits. Hilgard at first also held this view, but after studying the north Louisiana salines concluded that they represented the peaks of a Cretaceous ridge trending in a northwesterly direction across the state and buried by the flat-lying Tertiary beds. Lerch's later explanation is simply a modification of Hilgard's, for he suggested a highly faulted and folded Cretaceous ridge elevated by "plutonic forces" and later buried by Tertiary sediments; and Clendenin advocated a similar view. As Veatch's work in the late nineties soon developed the fact that extensive movements had taken place around the domes in Tertiary time, these theories are no longer regarded as tenable.

The theories recently advanced by Norton and Kennedy take little account of the intense structure around the domes and hence in the writer's opinion constitute a backward step. Norton postulates thermal springs depositing travertine and salt and building up these deposits as fast as the surrounding plain was being built up by sedimentation. His special attempt to explain the limestone of the cap rock as travertine is noteworthy, but he does not account for the precipitation of the salt from solution and dismisses the structure as "no doubt due to faulting and downward displacements." Kennedy explains the salt as a deposit in old ponds or lakes into which thermal springs discharged. Neither the shape and depth of the salt mass, the mode of precipitation of the salt, nor the structural disturbances are accounted for.

Igneous Theories.[22]

The remarkable structural disturbances which characterize the domes have led several writers to ascribe them to igneous intrusions. Hager and Veatch arrived at this conclusion independ-

[22] An excellent summary of the theories that connect the domes with igneous activity and a critical review of these theories, with an adverse conclusion, has just been published by De Golyer, E. L., "The Theory of Volcanic Origin of Salt Domes," Am. Inst. Min. Eng. Bull. 137, p. 987, 1918.

ently and Lucas has recently suggested a somewhat similar theory. In fact in 1903, before any of these theories were advanced, Coste had referred to the domes as phenomena of the "solfataric phase of vulcanism," but he adopts this interpretation without debate and uses it chiefly as an argument for the inorganic origin of oil. Several others, notably Thomassy, Norton, Washburne, and Turrentine, also postulate igneous intrusions as indirect causes, but their hypotheses may be discussed more conveniently under other headings.

The chief points in favor of the igneous hypotheses are that they account for the upthrust so characteristic of the domes, explain the rather high temperature of the waters, and in a measure account for the common presence of sulphur and metallic sulphides in the cap rock. Igneous intrusions of Cretaceous age are not uncommon along the old Upper Cretaceous shore line in central Texas and southern Arkansas, and one small igneous plug of late Tertiary or Quaternary age has recently been discovered between the coastal domes and those in northern Texas. Volcanic ash has been found in the Tertiary sediments on the flanks of some of the domes, though it may of course have been transported from a considerable distance. On the other hand, if the domes are due to igneous intrusions, it is strange indeed that no igneous rocks (or sedimentary rocks altered by igneous action) have been encountered in the many deep wells drilled, especially since, according to this theory, a separate and distinct plug must occur beneath each dome. If it be admitted, however, that igneous rocks do not approach within 4,000 or 5,000 feet of the surface, it is difficult to see how they could have been the direct cause of such sharp upthrusts, and the principal reason for assuming their presence, according to the theory, is thus obviated.

Another and graver objection to the simple igneous theory is the fact that it does not explain the source of the salt or the cause of its precipitation. It is true that hydrochloric acid and various chlorides have been observed around some volcanoes and may perhaps be associated with some igneous intrusions; but it is also true that in all known volcanoes these substances occur, if at all, in very minor amount and that they are invariably subordinate

to some other emanations, such as sulphur. Even if it be granted, then, that igneous intrusions are capable of giving rise to these enormous masses of salt, the problem of explaining the absence of the other emanations still remains, for although sulphur is abundant in two or three of the domes, its bulk, compared to that of the salt, is very small. Veatch did not undertake to explain the source of the salt, however, and Hager contents himself with stating that "heated waters from great depths found vent along the same channels, carrying in solution carbonates of lime and magnesium, gypsum, and salt." If these hypothetical waters and their dissolved salts are supposed to be unconnected with igneous intrusions then the hypothesis partakes of the nature of those discussed below and shares the same objections.

Theories of Secondary Deposition from Artesian Waters.

Theories which postulate the deposition of the salt from artesian waters ascending along lines of weakness have been elaborately developed and are probably the most widely accepted by American geologists to-day. G. D. Harris, whose intimate knowledge of the Louisiana domes commands especial respect, has been the most able and active proponent of this type of theory. Harris[23] summarizes his views as follows:

> There is no reason why waters entering the pervious layers far up country should not go down to greater and greater depths as the latitude of the Gulf border is approached. Such waters might reach considerable depths, be raised accordingly to a high temperature and take in solution many salts, especially chloride of sodium. Ascending under hydrostatic pressure at the above-mentioned points of weakness and cooling normally at the rate of 1° C. for every 90 feet of ascent, a point would be reached where the solution, if saturated at a high temperature, could no longer retain all its salts. Precipitation would begin, rapidly at first, but decreasing slowly as cooler surface temperatures are reached.
>
> With precipitation of salt would naturally go crystallization. The power exerted by growing crystals (in general) may be assumed to be of the same order of magnitude as the crushing strength of the crystals themselves. We have subjected a four-inch cube to a pressure of 50,000 lbs. without even cracking it. Tournaire crushed cubic centi-

[23] Econ. Geology, Vol. 4, pp. 21–23, 1909.

meters of rock salt with pressures of from 332 to 461 kilograms. If the specific gravity of Quaternary clays and sands be taken as 2.4, then growing salt crystals could lift up 3,000, 4,000 or even 5,000 feet of such incoherent strata.

This theory has several weak points, one of which has been pointed out by several writers.[24] The effect of decrease of temperature on the solubility of salt is small, and that of decrease of pressure is still smaller. One hundred parts of water can carry forty-five parts of sodium chloride in solution at 180° C., thirty-nine parts at 100°, and thirty-six parts at 15°. If it be assumed that the solution became saturated and started to rise from a depth of 7,200 feet, where its temperature would be 100° C., it would lose only three parts or about 8 per cent. of its total load, and for every ton of salt precipitated over 11 tons must have escaped. In the Humble dome at least 66 billion tons of salt have already been blocked out (by wells drilled primarily for oil). This represents all the salt in 410 cubic miles of sea water or in 38 cubic miles of a saturated solution at 30°; but as this would be, according to Harris, only 8 per cent. of the salt involved, then some 750 billion tons, forming about 450 cubic miles of solution, must have escaped. When we consider that Humble is simply one of scores of domes, each of which would involve the movement and escape of a similar quantity of fluid and salt, the theory seems rather incredible.

The manner in which the bulk of the saturated solution (450 cubic miles at Humble) escaped is not considered by Harris. If it flowed out over the surface, as would seem natural, it is exceedingly difficult to understand why some evaporation did not take place, causing the formation of smaller bedded deposits of salt. Yet not even salt water is found in the sediments to considerable depth, except close to the domes and in a belt along the coast. As some of the domes have grown within recent times and are probably still growing to-day, we should expect to find great volumes of saturated salt solutions issuing from them, yet only minor seeps of relatively dilute character are known. In

[24] Lindgren, W., "Mineral Deposits," p. 288, 1913; Turrentine, J. W., *loc. cit.*; Washburne, C. W., *op. cit.*, p. 379.

fact tremendous springs of saturated salt solution, such as Harris's theory requires, are not common on the earth to-day, if indeed they occur at all; large springs, it is true, issue from the Balcones fault zone in central Texas but the water is cool and potable. To assume, on the other hand, that the solution did not issue from a surface spring but simply approached the surface, dropped its salt, and escaped underground to the sea through some convenient porous stratum, is too fanciful for credence.

Harris's explanation of the common occurrence of gypsum above the salt is not at all convincing. The solubility of $CaSO_4$ in fresh water increases with chilling down to about 40° and decreases only slightly thence to 20°; it is about as soluble at 20° as at 50°. Ascending solutions, therefore, could not deposit at the surface any gypsum except that which they picked up above the 50° zone, and as the waters were confined to pretty definite channels while passing up through this zone, the first waters to rise must soon have exhausted whatever gypsum was present along their course. Harris, however, points out that the same solutions carried both the gypsum and the salt and that with decrease of salt below 14 per cent. the solubility of the gypsum is also decreased. This might explain the precipitation of the gypsum, it is true, except for the fact that no means by which the concentration of the salt could be reduced to 14 per cent. or indeed below 36 per cent. is suggested.

The soundness of the second main point of Harris's theory, that the uplift is due to the force of growing crystals, is at least debatable. Admitting that the force of growing crystals is in general of the same order as their crushing strength, it is nevertheless true that salt, as described on page 36, is one of the most plastic substances. A temperature of 100° C. or more, and probably also the presence of a little water, greatly increase its plasticity, and it is doubtful whether the sharp and sudden pressure used in a crushing test is a fair criterion of the power that would be exerted by the growing crystals. Dr. G. F. Becker, who first recognized the geologic significance of the force of growing crystals, and upon whose work Harris bases his contention, has written to the writer: "I do not for a moment believe that the

linear force of growing crystals has caused intrusion of salt plugs or doming of the sediments. It may to some extent have modified the action on the walls and have aided in causing distortions within the mass. Recrystallization of the salt *in situ* would obliterate strains in such crystals."

If the force of growing crystals were sufficient to dome the overlying sediments, it would seem to be sufficient also to prevent further ascent of the solutions, for their head or pressure, being artesian, must have decreased as they approached the surface. When gas wells become plugged with salt (through the evaporation of brine by the expanding gas) they automatically shut off their own gas pressure, which may amount to 500 to 1,000 pounds per square inch. Assuming that the ascending brine solutions were under sufficient hydrostatic head to just reach the surface, this would be equivalent to their hydrostatic pressure at a depth of 1,150–2,300 feet; in other words, the deposition of enough salt to plug the orifice above such depth would simply overcome the pressure and stop the ascent of the solutions, or else force them to seek new channels. If they sought new channels the salt deposits would be a series of plugs, partly intergrown, perhaps, but with inclusions of sedimentary rocks between them; and their combined areal extent would be great in proportion to their vertical dimensions.

Realizing a vital weakness of Harris's theory, viz., the vast quantity of salt involved, several writers have undertaken to modify it by introducing a precipitating agent or condition more efficient than simple cooling. Washburne points out that sodium chloride may be precipitated from concentrated solution by mass action due to the addition of a common ion, and suggests that the salt solution may have mingled with solutions carrying other chlorides of magmatic origin. Theoretically, hydrochloric acid or calcium and magnesium chlorides would act as effective precipitants of sodium chloride, and if their influence could be proved this hypothesis would be very plausible. Washburne's argument, however, was based on the high percentage of calcium and magnesium chlorides in Appalachian oil-field waters, and it now appears that the salt-dome brines are abnormally low in these chlo-

rides. Turrentine[52] gives six analyses of salt-dome brines in which the average ratio of chlorine to sodium is only 1.7 or less than in sea water, and the salt itself is also exceptionally free from calcium and magnesium chlorides. To this objection must be added the scantiness of chlorine in the emanations of most volcanoes, and the absence in the cap rocks of any minerals of volcanic or pneumatolytic origin except sulphur.

The precipitating agent proposed by Mills and Wells is of physical rather than chemical nature. Having observed in Ohio the plugging of gas wells by salt, deposited through the evaporation of brine by the expanding gas, they suggest that the salt domes may have been formed by a similar process on a larger scale. In other words, concentrated salt solutions ascending under artesian pressure may have mingled with gas escaping through the same orifice; the gas expanding under decrease in pressure would take up water vapor, concentrate the solutions beyond the saturation point, and so bring about precipitation of the salt. As a cubic foot of gas under atmospheric pressure can, however, carry only a small amount of water vapor, an enormous quantity of gas must be postulated in order to make this process effective. The recent sediments of the Gulf Coast are generating considerable quantities of gas, and after rains it may be observed bubbling up almost anywhere on the prairie. Such gas, for the purpose of the theory, is, however, lost; only that gas is effective which is collected and escapes with the brine along well-defined fissures. Furthermore, the Ohio gas wells are not strictly analogous to natural seeps, for in the wells the brine is present in very small and the gas in very large proportion; and this condition could be simulated in nature only by assuming that the flow of water was very small and that little of it escaped. Again, as already stated, the gas wells plug themselves off through this process, which, therefore, soon becomes inoperative or at least extremely slow. These difficulties, however, are subsidiary to the main problem of explaining the source and concentration of the vast amount of gas necessary, unless indeed igneous intrusion is postulated and the gas ascribed to magmatic sources.

[52] Turrentine, J. W., *op. cit.*, p. 60.

The theory has several other objections inherent in Harris's theory, as already discussed, and the writer is not inclined to accept it as a sole and sufficient explanation of the domes; yet if any theory of deposition from solution is to be adopted, the principles discussed by Mills and Wells must be considered of prime importance.

ORIGIN OF DOMES IN OTHER COUNTRIES.

The salt domes of Texas and Louisiana are not unique, and in considering their origin it is desirable to take into account the relations of apparently similar occurrences in other countries. Salt domes similar to those in Texas and Louisiana are found on the Isthmus of Tehuantepec, Mexico, and in northwestern Europe; and salt masses similar in many respects are found on the Carpathian region of southeastern Europe, and in India, Algiers, and many other countries. A brief summary of the characteristics of some of these domes and of the commonly accepted views as to their origin may be of interest.

Mexico.—The Tehuantepec domes are of especial interest because of their relative proximity to those in Texas and Louisiana and because of their practical identity in structure and composition.[26] Many of the Tehuantepec domes, like those in north Louisiana, are marked by a depression surrounded by a circular escarpment. The strong upthrust is further indicated, at a dome near Chinameca, by small blocks of Jurassic or Cretaceous limestone which have been brought to the surface amidst the Tertiary and Quaternary sediments. The chief point of difference between the Texas-Louisiana and the Mexican domes is the more marked tendency of the latter toward elongation or anticlinal form; and De Golyer states that the structures produced by the salt masses generally resemble folds, which may often be traced from one dome to another.

Northwestern Europe.—Although the salt domes of northwestern Europe are far removed from the Texas-Louisiana

[26] De Golyer, *op. cit.*, p. 998; Hartley, Burton, "The Petroleum Geology of the Isthmus of Tehuantepec," ECON. GEOLOGY, Vol. 12, pp. 581–588, 1917; Moon, F. W., *Trans. Inst. Min. and Met.* (England), Vol. 20, p. 250, 1910–11.

domes and occur under somewhat different conditions, the fact that they have been much more thoroughly studied lends especial value to conclusions as to their origin.[27] The confidence with which these conclusions have been expressed lies not only in the fact that many of the domes have been extensively core-drilled in the search for potash, but also in the fact that only slightly deformed bedded deposits occur and are mined in the same general region, so that their relations to the true salt plugs or domes may be clearly worked out.

The European domes, like those in Texas and Louisiana, occur along well-defined structural lines and are located in a plains region of practically flat-lying Cenozoic sediments. The domes are generally circular or elliptical in plan and consist of a plug of salt capped by debosits of limestone, gypsum, and anhydrite. The salt normally occurs as thick-bedded deposits in Permian basins, now covered by Mesozoic and Cenozoic strata. Deformation has been especially severe in the deeper central parts of these basins, so that although the surface strata are only slightly affected, if at all, the Permian has been folded and broken into a series of fault blocks. Around the edges of the basins the salt lies fairly close to the surface and its bedded character is unmistakable, but even here it may be intensely deformed along structural lines and may have locally pierced the overlying formations and formed short salt plugs or domes.[28] Where the Permian lies deeper beneath the surface the plugs are longer and only their tops can be reached by drilling, but the relations of this salt to the main bedded deposits below are attested by blocks of Permian and Mesozoic rocks that have been brought up with it.

[27] During the past twelve years especially these domes have been actively studied and explored and the literature describing them and discussing the mode of their formation is now very voluminous. A good review of the literature to 1912 is given by Hahn, F. F., "The Form of Salt Deposits," Econ. Geology, Vol. 7, p. 120, 1912. Van der Gracht, who took an active part in the core drilling of many of the domes, has contributed a valuable brief description: "The Salt Domes of Northwestern Europe," Southwestern Assoc. Petroleum Geologists Bull. 1, p. 85, 1917.

[28] See for example Schüneman, F., "Vorläufige Mitteilung über einzelne Ergebnisse meiner Untersuchungen auf den Kaliwerken des Stassfurter Sattels," *Zeits. f. prak. Geol.*, Vol. 21, p. 205, 1913.

There are numerous salt plugs within 800 feet of the surface in Holland and northwestern Germany where the Permian normally lies at depths of 16,000 to 22,000 feet, and some of them are marked by red Permian rocks brought up with the salt and now forming isolated outcrops in the Quaternary plain.

As the derivation of the European salt domes from a Permian bedded deposit now appears to be indisputable, theories of secondary deposition from ascending waters are no longer held, but a highly polemical controversy has arisen over the mechanics of the salt intrusion. Von Koenen, Everding, Stille, and others at first regarded them as simply folds, the nucleus or core of which had pierced through the overlying formations. Harbort emphasized the plasticity of salt and concluded that it had risen through fissures like a molten magma under the pressure of orogenic forces. Arrhenius and others point to the low specific gravity of salt and suggest that it has been forced up by the weight of the overlying sediments—a purely isostatic conception. Lachmann has endeavored to effect a compromise, inclining toward isostasy as the chief force, but dwelling on the plasticity, power of recrystallization, and other properties inherent in the salt itself.

Roumania.—The Roumanian salt deposits on the south front of the Carpathians are also instructive, for as they occur in a region of considerable relief and good exposures, their relations may be studied at the surface. The structure and distribution of the salt-bearing formation—the Salifère—has an important bearing on the occurrence of the petroleum and has been thoroughly worked out by Professor Mrazec and his associates.[29] The rocks involved are of Tertiary age; the Salifère (Lower Miocene) consists of a great thickness of gypsum, clay, and marl, containing huge lenses of salt; the overlying Upper Miocene, Pliocene, and Quaternary, which range in thickness up to 8,000 feet, consist of unconsolidated clays, marls, and sands. The disturbance of the foothill belt has been very intense, owing to the lateral

[29] Mrazec, L., and Teisseyre, W., "Aperçu géologique sur les formations salifères et les gisements de sel en Roumaine," Mon. des intérêts pét. Rou. Nos. 43–51, January–June, 1902; Mrazec, L., "L'Industrie du Pétrole en Roumanie," Bucarest, 1910.

pressure of the rocks of the foreland; the salt-bearing formation, especially, has been extensively underthrust and in many places now lies in a series of faulted and overturned folds resting upon the younger formations. A peculiar characteristic of the structure, however, is the tendency of the Miocene beds, and especially the salt formation, to pierce through the overlying rocks at certain points on anticlinal axes, thus giving rise to a structure so common that Mrazec has coined the term "diapir fold" to describe it.[30] (See Fig. 55.) In many instances the salt core has pierced through more than 7,000 feet of overlying sediments and now outcrops at the surface, usually in an elliptical form inter-

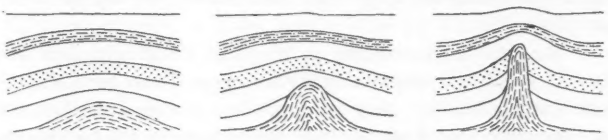


FIG. 55. Development of diapir structure, symmetric type. (Ater Mrazec.)

mediate between a pierced anticline and a true salt dome. When movement of the underthrusting blocks has continued sufficiently far, however, the lower part of the salt core has been squeezed out entirely and the salt occurs "as an isolated and unrooted mass—a klippe." Hence in Roumania, even more plainly than in northwestern Europe, the salt domes or plugs are the result of tectonic forces, though it is recognized that the salt, owing to its peculiar properties, has reacted to these forces in a manner somewhat more pronounced than the surrounding sediments.

INTRUSIVE THEORY OF THE ORIGIN OF THE DOMES.

General Statement.

The writer is inclined to believe that the Gulf Coast salt domes, like those in northwestern Europe and Roumania, are offshoots of bedded salt deposits, formed and forced upward by pressure in a semiplastic condition. The chief points in favor of this hy-

[30] Mrazec, L., "Les plis à noyaux de percement," *Bull. Soc. sci. Bucarest*, 1906.

pothesis are: (*a*) the sharp local doming of the sediments above the salt—doming of a type which several writers have stated is known to have been produced elsewhere only by (igneous) intrusion; (*b*) the flow structure, crystal orientation, and cleavage of the salt itself, indicative of pronounced movement in a vertical direction; (*c*) the plasticity of salt, which is considerable at ordinary temperatures and increases rapidly with heat; (*d*) the clear evidence that similar domes in other countries have actually been formed under the conditions postulated. On the other hand it is necessary to show, (*a*) the possibility that bedded salt deposits exist at depth beneath the Gulf Coast; and (*b*) the possibility that forces competent to produce the results observed have been operative.

As the structures produced by the Gulf Coast salt plugs and also the nature and relations of the European domes have already been briefly described, they need not be considered further. It may be pointed out, however, that the piercing of the Catahoula-Fayette sands at Humble by the Yegua formation, and the later piercing of the Yegua by the salt itself, is an example of diapir structure in every way analogous to that observed in the Roumanian fields; and that the block of Jurassic or Cretaceous limestone brought up through Tertiary and Quaternary sediments by one of the Tehuantepec domes is an example of the structures common in northwestern Europe. It is also noteworthy that two of the foremost authorities on the European domes—Professor Mrazec, Director of the Geological Survey of Roumania, and Doctor Van der Gracht, late Director of the Geological Survey of Holland—have studied the coastal domes and regard them as genetically similar to the European occurrences.[31]

Structure of the Salt in the Domes.

Although the broader relations of the Gulf Coast domes have been emphasized by most previous writers, the structure and texture of the salt itself have received but little attention, except from Harris. Many wells have penetrated the salt at one dome

[31] Both geologists have expressed this conviction to the writer in conversation; Van der Gracht has also stated it indirectly in the paper cited.

or another and samples of many cores are available for study; but the most instructive observations are to be made at Averys and Weeks Islands, Louisiana, where the salt is being mined and where its structure may be studied in place. In both of these mines the pure salt is quarried out at a depth of over 500 feet below the top of the salt mass; no foreign material has been found in either mine, save for a little mass of red sandstone encountered in the Averys Island mine and described below.

At the salt mines and in most of the other domes the salt occurs as a fairly coherent mass of interlocking crystals, generally one fourth to one half inch in diameter At a few of the Texas domes the salt is more finely granular and so incoherent that it can scarcely be cored; on the other hand large transparent crystals are sometimes found in the mines but are not very common. The ordinary small crystals are irregular and poorly formed, but generally have one axis one and a half to two times as long as the others; and in general the long axis is more or less vertical. The salt mass as a whole, however, appears in the mines to have a rough horizontal cleavage, so that the roofs of the huge chambers from which it is quarried out are fairly regular and even.

The salt is not entirely homogeneous, but in places contains streaks or bands of a darker variety, which, according to Harris, contains about 3 per cent. of anhydrite in very small crystals.[32] In a hand specimen the two varieties can scarcely be distinguished. but in the walls and roofs of the chambers the darker streaks stand out prominently. In the vertical walls the streaks are commonly parallel and dip at angles greater than 70°, as shown in Plate XXXIII.; in the roofs they are commonly folded or contorted in a manner strongly suggestive of the flow structure of a marble or the shear structure of a gneiss. Examples of this structure are shown in the accompying photographs. Plate XXXIV., *A,* is a photograph of the roof directly above the wall shown in Plate XXXIII., *A;* in other words the axis of this fold is vertical, its cross section appearing on the horizontal plane, and the trace of the folded streaks appearing on the vertical plane

[32] Louisiana Geol. Survey Bull. 7, p. 16, 1908.

Plate XXXIV., *B*, is also a picture of the roof and represents a similar vertical-axis fold, the streaks in the wall below it being almost vertical and parallel. Plate XXXVI. shows a fold whose axis is more nearly horizontal, and XXXV. is a photograph of a hand specimen of plicated schist, inserted for the purpose of comparison. On an irregular working face which cuts the streaks at various angles all kinds of odd contortions may be observed, occasionally even perfectly circular or concentric markings which presumably represent the cross sections of little domes.

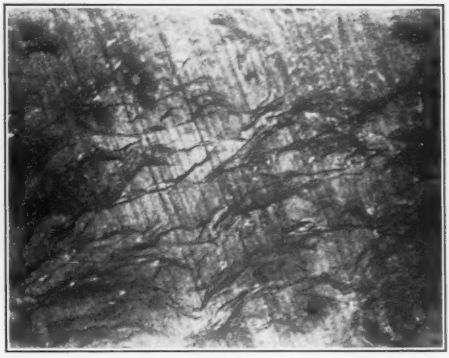
Although the course of the parallel streaks shown in Plate XXXIII. is not constant, they appear to have a fairly definite arrangement. Their dip is most commonly almost vertical and at no point observed is less than 60°. Their strike is less regular, but in those chambers in both mines which lie nearest the edge of the salt mass the streaks trend roughly parallel to the edge. In the chambers farthest in, the strike is more variable, but in the Weeks Island mine is roughly normal to the strike near the edge. Harris concluded, however, that all the streaks in the Weeks Island mine trend more or less parallel with the nearest (the south and west) flanks of the salt mass, and that this "would indicate that the form of the salt mass has something in common with the formation of the streaks."

In discussing the origin of the domes Harris explains the streaks as due to variation in the composition of the solutions which deposited the salt.[33]

> These streaks, often very faint, have been spoken of usually as lines of stratification. But they seem not to be such on close examination. Their vertical, or nearly vertical position in many places of course would not debar them from being true bedding planes, for it is quite conceivable that some salt strata have been highly tilted and much deformed. But there are concentric circular figures alone in white banks of salt that look more like slight discolorations due to the infiltration of waters carrying impurities. The crystals about such places show, so far as we can see, no signs of torsional stresses.

[33] Louisiana Geol. Survey Bull. 7, pp. 76–77, 1908.

A.



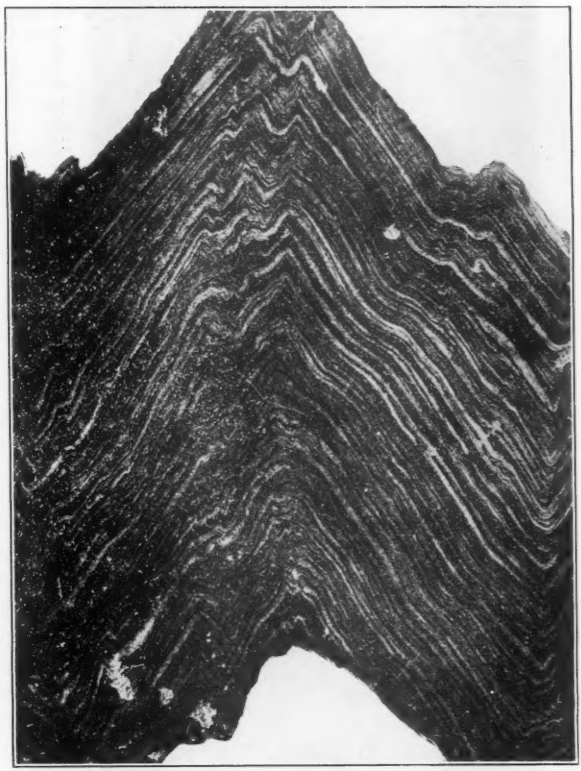
B.

A and B, Flow structure in the salt, Avery Island mine, Louisiana. The streaks appearing in the walls of the mine are usually parallel and nearly vertical, as shown in the photographs.

A.

B.

Flow structure in the salt, Avery Island mine, Louisiana. A, Roof adjacent to wall shown in Plate XXXIII., A. The fold thus has a vertical axis, its cross-section appearing on the horizontal plane and the trace of the folded members on the vertical plane. B, Roof, showing vertical axis folds. (Photograph by Veatch.)



Mica schist (hand specimen). Inserted to show similarity in type between the plications of schist and the contorted folds in the salt.

Flow structure in the salt, Avery Island mine, Louisiana. View of wall, showing fold with inclined axis.

Again, in a later paper, he says:[34]

> In an ordinary salt cone there should be growth not only on the bottom, but also on the sides. The ascending saline solutions would naturally vary somewhat as slight movements took place in the deep-lying beds below and northward from any dome-forming area. These variations would be apparent in the salt as nearly vertical streaks or layers when the mass is exposed in the huge chambers of salt mines. These streaks, then, may be regarded as layers of exogenous growth rather than ordinary bedding planes highly inclined.

Harris thus emphasizes the parallel vertical streaks and the occasional concentric markings, but apparently does not consider the common highly contorted folds so suggestive of flow structure. If the salt had been simply folded under moderate pressure like a Tertiary sandstone, for example, we should, it is true, expect to find only the parallel streaks marking the limbs of the fold, and concentric patterns would be inexplicable. But if it be recognized that salt under great pressure behaves as a highly plastic substance, and if the salt be thought of as having been *intruded* into a constricted opening or weak point, then the nature of these markings becomes clear. Under these conditions all the complex flow and shear structure characteristic of ancient marbles or gneisses might develop; original stratification lines might be drawn out parallel for long distances or thrown into intricate folds, or in places into small domes whose cross sections would appear as circular patterns. The folds themselves might be overturned in almost any position, though the straight streaks should be roughly parallel to the direction of flow, or vertical, as they are in the mines. The general elongation of the salt crystals in a vertical direction also suggests flowage, while the rough horizontal fracture indicates pressure. The most striking and best evidence of movement, however, are the streaks themselves, and in the writer's opinion they can be interpreted only as true flow structure.

The only foreign substance yet encountered in the salt is a small slender mass of tough red sandstone in the Avery mine.

[34] Econ. Geology, Vol. 4, p. 25, 1909.

The mass stands almost vertical and extends at least from the roof of the chamber to the floor, a distance of about 80 feet; it strikes about east and west and has been followed for about 75 feet, disappearing at one end but not at the other. It is extremely irregular in width, ranging up to 10 inches in some places and in others pinching out entirely. The rock, though tough, appears to be brecciated and contains many small fissures filled with salt. Under the microscope it is seen to consist chiefly of quartz crystals with a few fairly fresh feldspars. Some of the grains are very well rounded, but others are highly angular. Most of the quartz grains show evidence of strain and there has been considerable secondary enlargement, though hardly enough to warrant classifying the rock as a quartzite. The cement seems to be chiefly silica and iron oxide, but there is also an isotropic, yellowish, structureless substance which was not identified.

Advocates of the secondary deposition theories might possibly suggest that this sandstone represents sand which had fallen into a vertical fissure and had later been compacted; but the cement and the secondary enlargement of the quartz grains indicate circulation of ferruginous and silicious waters after the sand had become placed, and such waters could not have circulated through the salt mass without dissolving much salt and introducing much foreign material. Probably, therefore, the rock was cemented before it entered the salt mass. Furthermore, the vertical position of the sandstone mass and its irregularity in width—practical discontinuity—suggest that it has been dragged out under pressure, somewhat as an old pegmatite dike is dragged out in a schist or gneiss. It seems safe to assume that it represents a fragment of sandstone picked up by the salt in its upward course, but there appears to be no way of ascertaining the formation from which it was derived. In general appearance it does not resemble a Tertiary rock, while the red color of course suggests a Permian derivation, though little weight can be placed on such criteria.

Plasticity of Salt.

Laboratory experiments by several investigators have shown that salt crystals are easily deformed by differential pressure and that salt is a fairly plastic substance.

Although Reusch experimented on the plasticity of salt as early as 1867 the most widely quoted experiments are those made by Rinne in 1903.[35] Rinne placed prisms of transparent halite and sylvite in copper cylinders having walls 3 mm. thick, filled the remaining space with melted alum and subjected the cylinders and their contents to pressure for periods of 8 to 25 minutes. By using sufficient pressure it was found possible to flatten prisms of rock salt several centimeters high into irregular plates only a few millimeters thick, as shown in Fig. 56. If the pressure was

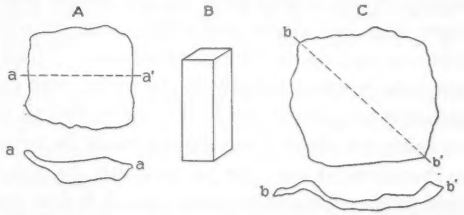


FIG. 56. Deformation of salt cleavage-fragments under pressure, showing plasticity of salt. (After Rinne.) *B*, type of original fragment; *A* and *C*, top and side views of two deformed fragments.

applied gradually, the deformed crystals were free from cracks and fissures and were just as strong and nearly as transparent as before being pressed; no double refraction was induced and the specific gravity remained unchanged. Adams[36] repeated this experiment in 1910 and compressed a 1.3-inch cube of salt into a

[35] Reusch, E., "Ueber eine besondere Gattung vom Durchgängen im Steinsalz und Kalkspath," *Pogg. Ann.*, Vol. 132, p. 441, 1867.

Rinne, F., "Plastische Umformung von Steinsalz und Sylvin unter allseitigem Druck," *Neues Jahrb. f. Min.*, Vol. 1, p. 114, 1904. See also Lehmann, O., "Plastische, fliessende und flüssige Krystalle," *Ann. d. Phys.*, Vol. 12, p. 311, 1903.

[36] Adams, Frank D., "An Experimental Investigation into the Action of Differential Pressure on Certain Minerals and Rocks Employing the Process Suggested by Prof. Kick," *Jour. Geology*, Vol. 18, p. 489, 1910.

plate .56 inch thick. He states that the flattened crystal was strong and brightly translucent; that its sides were in several places beautifully curved, and that the remarkable plasticity of the salt was shown especially by the perfect impression which it took of the sharp spreading end of the cylinder. He used a total pressure of 157,000 pounds, part of which of course was used up in the deformation of the cylinder. As Adams remarks, the fact that it is impossible to calculate the pressure actually used in deforming the crystal constitutes an objection to this type of experiment.

Equally interesting, though perhaps less exact experiments, have also been made by Milch.[37] He subjected slender prisms of salt to differential pressure at a temperature of 200° to 205° C. and was easily able to bend them into any desired shape. Some prisms were bent into circles and others were actually twisted several times around on their longitudinal axes. Milch's experiments have been repeated roughly by the writer, who finds that a bar-shaped cleavage piece of salt held by tongs half an inch above a Bunsen flame for about a minute can easily be twisted. Apparently, therefore, at 200° or so rock salt loses most of its rigidity and yields readily to pressure, though it does not actually melt below 800°. This type of phenomenon, especially with reference to the flow structure of the harder rocks, has been discussed by Johnston and his associates, who believe that such unequal pressure greatly lowers the melting point of any substance.

> Indeed if we make the plausible assumption that *permanent* deformation of a crystalline aggregate is conditioned by a real local melting (of those parts which at any moment bear the brunt of the load), we find the amount of pressure required to cause melting at ordinary temperature to be well within the bounds of probability.[38]

[37] Milch, L., "Ueber Zunahme der Plastizität bei Kristallen durch Erhöhung der Temperatur," *Neues. Jahrb. f. Min.*, Vol. 1, p. 60 ff., 1909; also "Ueber die Plastizität des Steinsalzes und ihre Abhängigkeit von der Temperatur," C. R. 12th Cong. Géol. Int., p. 891, Toronto, 1913.

[38] Johnston, John, and Adams, L. H., "On the Effect of High Pressures on the Physical and Chemical Behavior of Solids," *Am. Jour. Sci.*, 4th ser., Vol. 35, p. 251, 1913.

Two other observations on the properties of salt are of interest. Johnston and Adams state that when finely powdered dry salt is placed in a steel bomb fitted with a plunger and subjected to a pressure of several thousand atmospheres, the powdered salt becomes agglomerated into a solid block "sufficiently transparent to enable one to read print through it."[39] On the other hand an observation to which the writer's attention was directed by Dr. G. F. Becker indicates that salt possesses a property akin to ductility. This was discovered many years ago in searching for a substance with which to coat iron before drawing it into wire, and which would act as a lubricant and facilitate the passage of the metal through the dies. It was found that iron coated with salt might be drawn out through half a dozen diminishing dies and that the salt covering did not break or scale off, but stretched out concomitantly with the metal until it had become so thin that it was no longer visible and could be detected only by the taste.

It therefore appears that salt is distinctly plastic under stress and is ductile under tension; that it becomes still less rigid at a temperature of 200°; and that if crushed or powdered it easily becomes welded again into a coherent and transparent mass. The experiments establish these points beyond dispute, though unfortunately they give little idea of the pressure necessary to produce the results observed. From Adams's experiment, however, it is evident that distinct deformation is produced by a pressure considerably below 157,000 pounds; and it may be inferred that a much lower pressure acting during a period of years instead of minutes would have produced the same result. If an earth temperature of, say, 100° be also taken into account, the necessary pressure becomes still further reduced.

In considering the movement or flowage of salt in nature, however, it is evident that still another factor must be considered, viz., the presence of the small quantity of water which all salt contains. Students of metamorphic rocks have long recognized the potency of a small proportion of moisture in producing flow or shear structure by dissolving material from the strained face

[39] *Op. cit.*, pp. 228 and 233.

of the grain and depositing it upon an unstrained surface. It seems entirely reasonable to credit moisture with a similar rôle in the flowage of salt, especially within a few thousand feet of the surface where extra moisture would doubtless be picked up from the surrounding rocks. As Johnston suggests, however, the flowage of salt may be partly due to the real but temporary and local melting of those portions under greatest stress, and the process might thus be compared to the regelation of ice which accompanies the movement of a glacier.

Possibility of Bedded Salt Deposits beneath the Gulf Coast.

There is but little positive evidence either for or against the supposition that deep-seated bedded salt deposits exist in the coastal region. Wells penetrating 4,000 feet of Tertiary sediments have found no salt and it is evident that if any exists it is in the Mesozoic or Paleozoic rocks. No bedded salt deposits of any consequence are known to occur in the Cretaceous or Triassic beds and there seems little real basis for assuming their presence.

The Permian rocks of northwestern Texas and adjacent regions, however, contain important salt beds and a Permian derivation for the coastal salt, like that of northwestern Europe, therefore appears more plausible. According to well sections cited by Udden,[40] beds of salt aggregating 315 to 900 feet in thickness occur in the Permian of the Texas Panhandle. The basin in which these deposits lie, however, is bounded on the east by the belt of Pennsylvania strata outcropping in central Texas, and if similar deposits underlie southeastern Texas they must occur in another basin, whose existence can only be assumed. On the other hand, the Panhandle salt deposits disappear near the eastern edge of their basin, attaining their greatest thickness near its center; and the known absence of salt at shallow depths on the east side of the Pennsylvanian belt is no evidence that salt does not occur in the deeper central part of a basin, which would lie at unexplored depths. N. H. Darton,[41] who has investigated

[40] Udden, J. A., "Potash in the Texas Permian," Univ. of Texas Bull. 17, p. 51, 1915.

[41] Darton, N. H., Personal communication.

the deposits of the Panhandle, regards the existence of another and similar salt-bearing basin to the southeast as conjectural but entirely possible. Willis and Girty[42] in their map of North America during Permian time show the salt-dome area as "sea or land, more likely sea."

In view of the lack of positive evidence it is perhaps permissible to beg the question and argue that the best evidence of buried salt beds is the domes themselves. Most advocates of secondary deposition theories evade this point by assuming rather vaguely that the salt is derived from deeply buried strata, in which it occurred as connate water, or as concentrated brine, or as disseminated deposits. The supposition that the salt is derived from ordinary connate water[43] is not plausible and to postulate concentrated brines or disseminated salt is only a step from assuming bedded deposits. Harris[44] realizes this and apparently inclines to the belief that the salt is derived from bedded deposits:

> It is quite safe to say that the saline solutions spoken of above originate in the Mesozoic or Paleozoic beds beneath the Gulf coast Tertiaries, since the salt has not come from concentrating and sinking salt lakes. . . . There are no indications that salt-pan conditions prevailed in any Tertiary epoch, except perhaps locally in the upper Oligocene, and many of the salt masses in the northern "salines" are below layers of Cretaceous rocks. We feel, therefore, quite safe in saying that the primal, salt-pan-formed salt layers from which the Louisiana and east Texas

[42] Willis, B., and Salisbury, R. D., "Outlines of Geologic History," p. 177, Chicago, 1910.

[43] The volume of ordinary sea water required to produce the salt is extremely great. Sixty domes, each containing only the quantity of salt already blocked out at Humble (66 billion tons), require 4,000 billion tons, which represents the complete evaporation of about 25,000 cubic miles of sea water. Assume that one third of the rocks consist of material coarse enough to allow an appreciable movement of water and that this material has a porosity of 30 per cent.; then the whole section has an average porosity of 10 per cent. The 25,000 cubic miles of sea water would saturate 250,000 cubic miles of rock, or a block 2 miles deep, extending from Matagorda, Tex., to Assumption, La., and stretching from the coast northward to central Arkansas and Oklahoma, where the Paleozoic rocks outcrop. On the other hand if we accept Harris's theory of deposition from saturated brine, 90 per cent. of which escaped, enough saturated brine to fill the pores in an equal block of strata would be required.

[44] Harris, G. D., ECON. GEOLOGY, Vol. 4, pp. 28–30, 1909.

domes are formed in a secondary manner are probably early Mesozoic or late Paleozoic.

As late Permian beds are known within a comparatively short distance of the coastal area, and as the late Permian was an arid period in this region, just as in northwestern Europe and elsewhere, it does not seem unreasonable to assume the existence of Permian salt deposits beneath the Gulf Coast.

Geologic Structure of the Salt-Dome Region.

The region in which salt domes are known lies in the southwestern corner of the great triangular area of Tertiary and Quaternary rocks usually referred to as the Mississippi embayment. The surface formations in this area are in general practically undisturbed and dip coastward at angles slightly greater than the slope of the land. Except for the local disturbances around the salt plugs themselves, the only important uplift known in the area is the Sabine uplift in northwestern Louisiana. In the Cretaceous rocks bordering the area on the northwest however there are two well-known fault zones: the Balcones fault, which follows the Cretaceous-Eocene contact, trending in east Texas about north-northeast, and the Red River fault in north Texas, the strike of which is about east-southeast. The Red River fault is supposed to continue eastward into Louisiana and probably to connect with the Alabama Landing fault in the northeastern part of the state.

The striking arrangement of the salt domes on lines trending roughly parallel to the Balcones and Red River faults has been emphasized by Veatch, Harris, and other writers as indicating the common relation of the domes to deep-seated lines of deformation. The alignment of the domes has been described many times and the following summary of Harris's conclusions will suffice.

To suppose for an instant that the orderly rectilinear mode of occurrence of the saline domes is merely the work of chance is extreme folly. . . . Clearly, the varied wrenching and warping suffered by the rocks of this great delta region have given rise—and naturally so—to

structural features more or less parallel to the shores of the old Cretaceous terranes to the northeast and northwest. In the opinion of the writer all the saline domes are located along lines of fracture in the deep-lying Mesozoic and Paleozoic rocks, and in general their location seems to be at the crossing of such lines.

More direct evidence of the existence of faults in the Paleozoic rocks is afforded by Paige's[45] study of the Llano-Burnet region, which is about 100 miles northeast of the Brenham salt dome and is the nearest area of older rocks. In this district there are many faults, which appear to be genetically related. According to Paige, all the faults are pre-Cretaceous; all of them, with one important exception, have a general northeasterly trend; most of them are straight for long distances; the greater number are vertical and movement along them has generally been in a vertical direction; and the throw ranges up to 1,800 feet. Paige concludes that "conditions point rather conclusively to compression as the cause of the faulting."

Although the surface formations in the coastal region are practically flat and undisturbed, there thus appears to be pretty good evidence for assuming the presence of old lines of weakness in the Paleozoic rocks. During the filling of the Mississippi embayment and the warpings which accompanied its uplift it seems entirely probable that movement was revived on some of these old fractures. As these rocks were then covered by many thousand feet of unconsolidated sediments, the actual fracturing would not extend to the surface, but it would be sufficiently well defined in the lower part of the column to control and localize the course of a plastic salt mass ascending under pressure.

Cause of Movement of the Salt.

The writer has attempted to show that it is reasonable to assume that bedded salt deposits underlie the Gulf Coast at a depth of 10,000 to 20,000 feet; that salt under the pressures and temperatures to which such deposits would normally be subjected is a relatively plastic substance; and that lines of weakness probably

[45] Paige, Sidney, U. S. Geol. Survey Geol. Atlas, Llano-Burnet folio (No. 183), p. 10.

exist along which the salt would rise if under sufficient pressure. Possible causes of the pressure remain to be considered. Three appear possible, igneous intrusion at great depth; the weight of the overlying sediments; and lateral or compressive thrust.

Deep-seated batholithic intrusion would appear to furnish an adequate source of pressure. It is not necessary to assume a separate and distinct intrusion beneath each dome; the simple displacement due to the ascent of one large plutonic mass would cause indirect pressure on all the deeply buried rocks within a wide area. This pressure would be relieved by the ascent of the salt along lines of weakness; and the salt, not the igneous rocks, would cause the structures observed at the surface.

The assumption that plutonic forces have been at work is not an incredible one and has already been made by several writers. Turrentine suggested that the salt itself had been intruded and forced upward in a molten condition; Washburne that deep-seated magmas had given rise to chloride solutions; and Norton that the intrusion of molten rocks into the Paleozoic sediments had initiated the ascent of salt-bearing solutions. In the writer's opinion these special results of igneous intrusion are not likely, and it is sufficient to recognize simply that such intrusions would cause great differential pressure, which would find partial relief in the upward displacement of the salt along lines of weakness. On the other hand there is of course no direct evidence of deep-seated igneous intrusion, and it is undesirable to postulate it if a simpler explanation can be found.

The suggestion that the plastic salt was forced upward simply by the weight of the overlying sediments has been elaborated by Arrhenius and accepted by Lachmann and some other European geologists.[46] Their calculations are based on figures of 2.15 as the specific gravity of salt and 2.40 as that of the overlying sediments; assuming perfect adjustment a 1,000-foot column of sediment would therefore balance an 1,116-foot column of salt,

[46] Arrhenius, S., "Zur Physik der Salzlagerstätten," *Medel. Frau Vet-Akads. Nobelinstitut*, Bd. 2, No. 20, 1912.

Lachmann, R., "Studien ueber den Bau von Salzmassen," *Kali Zeitschrift*, Vol. 6, pp. 342, 366, 398, 418, 1912.

and if the original salt bed were 10,000 feet deep the ascending column should theoretically rise 1,116 feet above the surrounding surface. It is recognized of course that such conditions would obtain only if the salt were a perfect liquid, and that its solidarity, its viscosity, the friction incident to its passage, and the force required partially to dome the sediments themselves all prevent the attainment of anything like complete adjustment.

Although isostatic adjustment may be a contributing factor it does not appear to be a force competent alone to produce the results observed. Unfortunately we do not know the elastic limit of salt, which must be exceeded before permanent deformation can be induced, but judging from the pressure used by Adams it must amount to many thousand pounds. Accepting the figure of 2.40 as the gravity of the sediments, a salt bed at 10,000 feet would be under a pressure of only about 10,500 pounds, and even with the temperature of 130° C., which might be expected at this depth, it seems doubtful whether the rigidity of the salt would be overcome. Furthermore, it is by no means certain that the gravity of the Gulf Coast sediments is as high as 2.40; Shaw[47] has recently made a half dozen determinations which indicate a considerably lower figure, and if further work proves them to be representative, appeal to the isostatic principle as an adequate explanation must be abandoned.

The supposition that the salt was forced upward by lateral thrusting of the deeply buried rocks appears most plausible, even though (as in Roumania) the surface rocks show no evidence of compression. The numerous faults in the Llano-Burnet region, the nearest area of Paleozoic rocks, are in Paige's opinion due to deep-seated compression with consequent uplift; and although these faults are pre-Cretaceous, there is reason to suppose that similar forces have acted more recently. The salt-dome region lies along a heavily loaded sea coast which has been subjected to an ever-increasing weight of sediments since early Cretaceous time. These sediments are now at least 10,000 and perhaps

[47] Shaw, E. W., "The Possibility of Using Gravity Anomalies in the Search for Salt-Dome Oil and Gas Pools," *Science*, New Ser., Vol. 46, pp. 553–556, 1917.

15,000 or 20,000 feet thick. The direct result of such overloading is downward pressure, but a well-recognized secondary result is lateral pressure toward the region from which the sediments came. As shown experimentally by Becker[48] many years ago, this pressure, viewed broadly, is considerable and must be taken into account in any general discussion of isostatic compensation. At the depths in question the rocks would of course not be plastic and no actual migration of material toward the land area would take place; but the lateral pressure might well be sufficient to buckle or shatter the harder rocks, and if one plastic member, like salt, were present, to squeeze it upward into the less rigid sediments above. Other causes of lateral pressure might also be suggested; it is not unreasonable to suppose, for example, that the older rocks lie in a geosynclinal basin and are thus naturally subject to compression; but further speculation is unprofitable.

Those who are familiar with the undisturbed surface sediments of the Coastal Plain may find it difficult to accept the view that the deeply buried rocks have been greatly stressed, but it is necessary to realize that the section involved is a very thick one and that it is composed of two types of rock. The Paleozoic and Lower Mesozoic rocks are well indurated and rigid, but they are overlain by many thousand feet of only slightly consolidated and relatively yielding and plastic clays, marls, and sands. Notable displacements in the rigid rocks might be absorbed in the plastic sediments as flexures, which would die out before reaching the surface. Precisely this condition is observed in northwestern Europe, where blocks of the rigid rocks have been carried far upward into practically undisturbed sediments. Borings in many other regions have shown that structure may become more intense with depth, even where the surface rocks are similar in character to those below. In fact it has been proven by drilling on the domes themselves that the structure becomes more intense with depth; the surface beds are practically flat, yet those at a depth of 2,000 feet may dip at angles greater than 60°. The

[48] Becker, G. F., "Structure of the Sierra Nevada," *Bull. Geol. Soc. America*, Vol. 2, pp. 70 to 74, 1890.

soft and yielding nature of the upper sediments also explains the fact that the salt has risen along lines, rather than planes, of weakness, and now appears as isolated plugs; it doubtless started upward in the harder rocks along planes of weakness, but on entering the more plastic sediments its ascent would naturally become more and more localized and irregular.

ORIGIN OF THE CAP-ROCK MATERIAL.

The origin of the anhydrite, gypsum, limestone, and sulphur which cap most of the domes is an obscure problem, toward the definite solution of which little progress has been made. This is perhaps partly due to the fact that most geologists have considered the origin of the cap rock as an integral part of the whole salt-dome problem and have assumed that the cap-rock materials were deposited by the same agencies that brought the salt. Those who postulate deposition of the salt from solution have naturally found it very difficult to explain the precipitation of these less soluble substances above the salt. Some regard the anhydrite and sulphur as having been produced by the action of hydrogen sulphide on limestone; others suggest that the sulphur is derived through the reduction of the anhydrite by hydrocarbons. Many reactions may be written, but positive evidence will probably be obtained only through a thorough petrographic and chemical study.

To the writer it appears that the cap-rock problem is more or less distinct from that of the origin of the domes, and although the tectonic theory does not explain the presence of the cap rock, it suggests one or two new possibilities. For example, anhydrite is associated with all bedded salt deposits and very probably overlies that from which the salt plugs were derived; it seems entirely possible that when the salt was squeezed up a portion of an overlying anhydrite bed was brought up with it, just as blocks of older rocks have been brought up by the European domes. Sulphur is also associated with some salt deposits[49] and may have ascended in the same way. Later action of circulating waters

[49] Hunt, Walter F., "Origin of the Sulphur Deposits of Sicily," ECON. GEOLOGY, Vol. 10, pp. 543–579, 1915.

may have changed the shape of the mass considerably, partially converted the anhydrite into gypsum, and deposited the limestone. On the other hand, the whole cap rock may reasonably be ascribed to the action of ordinary ground waters; such waters, percolating down through any one bed toward the sea, would find their progress arrested by the salt plug and the uplifted sediments around it, and might rapidly ascend into a cooler zone where some of their dissolved salts would be precipitated. The European view, that the cap represents the residue left by the solution of the upper part of the salt plug, should also be considered, though this theory does not well account for the presence of thick caps on some of the high domes, like Damon Mound, and for the absence of a cap on certain deeply buried domes, such as New Iberia. The great complexity of the physico-chemical transformations possible within moderate ranges of temperature in precipitates from sea water have been studied in great detail by Nernst and his associates. When more is known of the paragenesis and relations of the cap-rock material and salt of the coastal domes the investigations of the Berlin school may prove applicable, but to attempt to apply their results at present would be premature.

SUMMARY.

The origin of the great plugs of salt that occur here and there beneath the Coastal Plain of Texas and Louisiana is an obscure problem which has been a subject of much speculation. The small diameter of these plugs and their great depth (at least 5,400 feet in one case) indicate that they are not original bedded deposits. Nearly all American writers have adopted the view that the salt has been deposited by ascending brines, but the plausibility of this theory is injured by the stupendous quantity of brine involved, for no likely condition has been suggested under which the waters would deposit more than a fraction of their dissolved load.

Although direct evidence of the mode of formation of the salt plugs is scanty, there are several indications that positive tectonic forces have been involved. The plugs are arranged rather reg-

ularly along lines that are undoubtedly related to the main structural features of the region. Moreover, the plugs have caused a sharp and very local upthrust or doming of the normally flat-lying sediments, the uplift in some cases amounting to at least 3,000 feet. The surface beds may be only slightly disturbed, if at all, but down on the flanks of the salt mass dips of 60° or more are common and in some cases formations have been thrust clear through the beds that normally overlie them. Still more direct evidence is afforded by the structure of the salt itself; as seen in the mines the salt contains dark streaks which, though commonly standing almost vertical, are in places thrown into intricate folds which bear an extraordinary resemblance to the flow structures of ancient rocks. The common elongation of the salt crystals in a vertical direction and the rough horizontal cleavage of the salt also suggest vertical movement.

Laboratory experiments have shown that salt under differential pressure behaves as a highly plastic substance; that its plasticity is increased by heat; and that if shattered it is easily welded by pressure. In view of the field evidence cited, the writer believes that the salt plugs are offshoots of deeply buried bedded deposits which have been subjected to great pressure or thrust, and have been partially squeezed upward in a semiplastic condition along lines of weakness. As the region lies along a heavily loaded sea coast, the nature of the lateral thrust is not difficult to understand. The fact that the surface beds are undisturbed, except immediately around the salt plugs, is explained by the nature of the section—a series of indurated and rigid formations overlain by a great thickness of relatively yielding and plastic sediments. Indirect evidence of the origin of the plugs is also afforded by their identity in structure and composition with the European salt stocks, the tectonic origin of which is declared to be unmistakable.

DISCUSSION

This department has been established by the editors in order to afford to those interested in questions relating to economic geology an opportunity for informal discussion. Contributions are cordially invited either in the form of discussion of more formal papers appearing in earlier numbers or bearing upon matters not previously treated. Letters should be directed to the Editor, Sheffield Scientific School of Yale University, New Haven, Conn. The full name of the author should be attached to all communications.

THE IDAHO PENEPLAIN.

Sir: I have followed with great interest the discussion regarding the Idaho peneplain and its relation to the past erosion of ore deposits, the latest contribution to which is contained in an article by John L. Rich in the March number of the current year. At first glance the contribution by Mr. Rich appears to settle the matter for good and all, but, pondering over the subject, I have concluded that a word or two are still to be said for the Eocene age of that old erosion surface. The discussion at times grows animated and the various authors are perhaps inclined to claim a little too much for their respective pet peneplains.

I remember seeing a statement by Professor Blackwelder[1] to the effect that peneplains of Pliocene age are quite common in the West and citing among other occurrences the old Pliocene surface of the present Sierra Nevada. Now I have always thought that that erosion surface in which are carved valleys with sediments of Miocene and even Eocene age was certainly pre-Miocene. However, there is no doubt that the alternative, that is valleys filled with Miocene detritus with a subsequent peneplanation in Pliocene time of the surrounding landscape, would make an attractive office study.

Now, to revert to the principal subject—the high and greatly

[1] *Jour. Geology*, Vol. 23, 1915, p. 206.

dissected erosion surface of the mountain mass of central Idaho —it seems that the best way of attacking the problem is not the study of Miocene drainage lines, which are apparently cut in that peneplain, but the consideration of certain larger features.

In the first place the Payette lake beds in their relation to the dissected peneplain of the mountains to the north would seem to present a clear case. The age of these lake beds I held to be Miocene but Professor Knowlton says on the base of the fossil flora that it is Eocene. To any one conversant with the geological conditions about Boise it would seem a very forced conclusion to assume that the mountain surface to the north was much later than these beds.[2]

In the description of the Hailey district[3] a reference is made to an erosional depression filled with Miocene (or Eocene) deposits and covered with basalt and rhyolite which occupies a low position (elevation 5,500) near the edge of the Snake River valley and certainly far below the high erosion surface. This always seemed good evidence to me, though, of course, the old erosion surface is not so well developed in this region as farther north.

I would, however, claim with some insistence that nobody has a right to assert a Pliocene or Miocene age of the high peneplain without having critically examined the relation of the Columbia River lava to that surface, as exposed in the region of the western margin of the Clearwater Mountains.[4] The Columbia River lava extends here as a beautifully developed plateau at an elevation of about 4,000 feet in front of the Clearwater Mountains. The age of the Columbia River lava is generally conceded to be Miocene, it is certainly not younger. To the east of this the Clearwater plateau rises to elevations of 7,000 feet above the sea, and I am inclined to think that the evidence is complete that the molten lavas in successive floods buried the foothills and dammed the rivers, forcing them to seek new channels. It is clear that the crucial point of this argument is the Miocene or pre-Miocene

[2] U. S. Geol. Survey, Boise Folio, No. 45.
[3] U. S. Geol. Survey, Twentieth Ann. Rept., pt. 3, 1899, p. 197.
[4] U. S. Geol. Survey, Prof. Paper 27, 1904.

age of the basalt flows. But unless that can be disproved, the age of the Idaho peneplain stands as Eocene or older.

WALDEMAR LINDGREN.

Moscow, IDAHO, April 11, 1918.

Sir: I was much interested in Mr. Rich's article on an old erosion surface in Idaho, which appeared in ECONOMIC GEOLOGY for March, 1918.

I am not however quite in accord with his views as to the age of the Idaho peneplain, that is, late Miocene or early Pliocene, but am inclined to agree with Mr. Umpleby that the peneplain was formed in the Eocene, or at the latest in the early Miocene, for the reasons that follow:

The Columbia River basalt has been referred to the Miocene,[1] and if this is the case it gives a plane of reference in northern Idaho, where this series of flows borders the older rocks which form the Idaho mountain area. These rocks consist chiefly of granite and quartzite and the area in which they occur is considered to be a part of the same peneplain described by Mr. Umpleby in central Idaho. In the vicinity of Moscow the mountain summits show the same uniformity of elevation as in other parts of the state, although considerably lower than in the southern end of the mountain area, and are undoubtedly a part of the same peneplain.

In the basalt plateau, adjacent to the older rocks, the drainage is in a youthful condition, with broad, flat divides separating the streams. The upper courses of these streams are in the mountains, they then flow on the surface of the plateau, and their lower courses are in canyons cut in the basalt. The canyons in the lower part of the streams vary in depth from nothing, on the plateau where they start, to over three thousand feet on the Snake, Salmon and Clearwater Rivers. Between the heads of the canyons and the mountains the streams flow on the surface of the plateau in shallow alluvial valleys cut in the wind-blown silt that covers the plateau. In the mountains the streams follow more mature valleys than those cut through the basalt, which is

[1] Folio No. 86, U. S. Geological Survey, Geo. Otis Smith.

RELIEF MAP
OF
IDAHO

Constructed by
D. C. Livingston

0 25 50
Scale — Miles

1. Salmon Meadows
2. Long Valley and North Fork of Payette River
3. South Fork of Salmon River
4. Secesh Creek
5. Stanley Fasin
6. Lost River Valley
7. Little Lost River and Pahsimeroi Valleys
8. Lemhi Valley
9. Salmon River
10. Middle Fork of Salmon River
11. Pasalt Plateau

shown by the more gentle slopes and soil-covered surface. The above characteristics can be plainly seen by referring to the enclosed photograph of a recently constructed relief model of the state of Idaho.

The Miocene basalt flowed up the old stream channels until stopped by the gradient, and in many cases dammed the streams and formed lakes, into which sediment from the adjoining mountains accumulated. These lakes were drained by the streams cutting through the basalt, leaving meadows or timbered flats which are bounded on their lower ends by a basaltic rim through which a canyon has been cut by the stream. Many of these filled lake basins exist along the borders of the mountain area, one of the best examples of which is Santa Creek, a tributary of the St. Maries River, and another is Tyson Creek, a tributary of the same stream. In the latter the lake beds at the head of the meadow have been exposed by placer mining and consist of partly consolidated clay. These deposits must therefore be more recent than the Miocene basalt but are not very extensive and do not show evidence of sufficient erosion to account for the formation of a peneplain in the high lands to the east.

The mountain country adjoining the basalt plateau is in the same condition of mature erosion as the mountains of central Idaho, although not as deeply dissected. If the basalt underlying the plateau is of Miocene age the erosion of the plateau must have taken place since that time and has not yet advanced beyond the youthful stage, as shown by the topography. It seems inconceivable that the adjacent mountain country could have been reduced to a peneplain, and that peneplain elevated and eroded to a condition of maturity, while the drainage system of the adjoining plateau did not advance beyond a condition of youth. This is what must have happened if the peneplain was formed in the Miocene period or later, as put forward by Mr. Rich, otherwise the age of the Columbia River basalt is incorrect.

If the Columbia basalt is of Miocene age, as is generally accepted, and if the peneplain was formed later, there should be extensive sediments lying upon the basalt, brought there by the

streams that drained the peneplain to the east. With the exception of the insignificant deposits of the intermontane lakes already mentioned, the writer has observed only one old stream channel. This channel however is overlain by the basalt and has been exposed by the erosion of the Snake River about two miles above the mouth of the Grande Ronde River, on the Washington side of the Snake. It lies at an elevation of about two thousand feet above the river and consists principally of water-worn boulders up to several feet in diameter. The boulders consist principally of quartzite but among them are many decomposed granite boulders containing biotite mica in considerable amounts. This would indicate the typical biotite granite or monzonite of central Idaho, and would be proof that the stream came from that direction. The same river wash is reported to occur on Craig Mountain, on the Idaho side of Snake River, and evidently represents the channel of a large stream that probably drained the peneplain in the Eocene or early Miocene period. The fact that this stream channel underlies basalt would seem to offer convincing proof that it antedated at least a part of the Miocene flow. The wash appears to lie upon a series of sediments consisting largely of limestone, in which the Snake River has eroded its channel at this place, and which may possibly be a part of the Triassic series reported to occur in the Seven Devils Mountains, Idaho, and in eastern Oregon.

Mr. Rich's objection to Mr. Umpleby's theory in regard to the age of the Idaho peneplain seems to be based largely on a different interpretation of certain facts in Lemhi County. The writer is not sufficiently familiar with that region to venture an opinion except in a general way but would like to bring forward a few facts which a study of the relief map of Idaho reveals, and which may possibly throw some light on the subject. First, the absolute lack of regularity in the drainage system of the Salmon River and its tributaries. For instance, Secesh Creek, one of the principal tributaries of the South Fork of the Salmon River, heads within a few miles of the main Salmon River and flows southeast into the South Fork, which flows northeast. The Middle Fork and South Fork of the Salmon both point upstream

where they enter the main river. The South Fork of the Salmon parallels for at least fifty miles the North Fork of the Payette River which flows due south while the former stream flows nearly due north. There are other examples too numerous to mention, but these irregularities would not indicate an earlier drainage system entrenched by the elevation of a peneplain.

Second, there are several structural valleys south of the Salmon River, which have a general course of a little to the west of north, and doubtless others have been destroyed by erosion. Taken in order from west to east across the state they are: Salmon Meadows, at the head of the Little Salmon River; Long Valley, on the North Fork of the Payette River, with Payette Lake at its head; Bear Valley, on the Payette River; Stanley Basin, to the east of the Sawtooth Mountains; Lost River Valley; Pahsimeroi and Little Lost River Valleys; and Lemhi Valley. Two similar structural valleys occur just outside the state line, the Bitterroot Valley in Montana, and Jackson Hole, Wyoming. The former has been formed by block faulting of the Bitterroot Mountains,[2] while a study of the topographic sheet, for that region, would indicate that Jackson Hole and the Teton Mountains had been formed in a similar manner.

The relief map also shows that the structural depressions in the mountain region north of Snake River possess a striking similarity in direction to the basin ranges south of Snake River. They would appear from this to be a northward extension of the block faulting of the Great Basin, which is supposed to have taken place in late Miocene or early Pliocene times, and it would be reasonable to suppose that the deformative movements to the north of the Snake River were initiated at the same time.

This would tend to eliminate the theory that Lemhi and Pahsimeroi Valleys were erosion valleys of the Peneplain as suggested by Mr. Umpleby. If these are structural valleys formed in late Miocene or early Pliocene times, there is no reason why the Salmon River should not be antecedent to the structure folds and have cut the deep canyon between Pahsimeroi and Lemhi Creeks while the folding or faulting was taking place.

[2] U. S. Geological Survey. Professional Paper No. 27. Waldemar Lindgren.

Summary.—The evidence in favor of an Eocene age for the Idaho Peneplain does not appear to be complete in the southern part of the state. In the northern part however the evidence seems to point strongly to this age, and if it is true there it must also be true in the southern part as well.

A study of the topography of central Idaho would suggest the following history: There was an elevation of the country in the Cretaceous or early Eocene due to the intrusion of the granite batholith, followed by a profound erosion of many thousand feet and the formation of a peneplain in the Eocene. The formation of this peneplain might possibly have continued into the early Miocene. This was followed by block faulting and igneous intrusions in the Miocene and Pliocene which resulted in a total rearrangement of the drainage system of the peneplain. Since the Pliocene the whole region has been reëlevated, resulting in renewed activity of the streams and the present rugged topography of the country.

D. C. LIVINGSTON.

REVIEWS.

Popular Oil Geology. By VICTOR ZIEGLER, Professor of Geology and Mineralogy, Colorado School of Mines. 149 pp., 63 figures and plates. 5 in. × 7½ in. × 7/16 in. Leather. C. H. Merrifield, Golden, Colorado, 1918. Price $2.50, postpaid.

This little volume, issued in convenient coat-pocket size, is an excellent handbook for all actual or prospective investors in oil properties or oil securities. It contains, within briefer compass than any similar manual which has appeared before it, a comprehensive though condensed treatment of the more important phases of modern oil geology. Even the most elementary principles involved are clearly and concisely explained, so that the book should be intelligible to the reader who is entirely without technical or scientific training.

The author gives evidence in many passages of a happy faculty of lucid exposition of essential principles, and even of moderately involved conceptions, in few words. This effectiveness is increased by numerous and well-chosen illustrations.

The book obviously is not intended for use as a text, nor would it be adequate as an aid in equipping a person for practical service as a field geologist; and it is to be hoped that none of its readers will obtain that impression. It is, however, well fitted to enable investors, or other interested persons, to understand better the principles upon which the trained geologist works, and the necessity of securing geological advice for any oil development, whether in wildcatting or in the management of a producing property. The last chapter contains some warnings which are very timely, in view of the great quantity of worthless stocks which have been floated on the basis of the Wyoming oil discoveries.

Brevity may have been carried a little too far in the chapter on structural geology, especially if the great importance of this subject is considered.

Oil developments and possibilities in Wyoming and Colorado are given special emphasis, and a chapter on oil shale is included.

The book would have been improved by more thorough proofreading, as minor errors, mostly typographical, are rather common. And one may be permitted to wonder whether the publisher has not overestimated "what the trade will bear" in fixing the price of the volume.

C. W. TOMLINSON.

SCIENTIFIC NOTES AND NEWS.[1]

PRESIDENT R. C. MACLAUREN, of the Massachusetts Institute of Technology, came to Washington in July to act as educational head of a students' army training corps, organized to give military instruction to student volunteers who are not yet of draft age.

THE COMMITTEE ON MINERAL IMPORTS AND EXPORTS has finished its work of formulating programs for the minimum importation of ores and minerals, and the members of the committee have taken up other work. Prof. C. K. Leith has been appointed mineral adviser to the War Industries Board from the standpoint of the conservation of shipping, Mr. J. E. Spurr is in charge of the war minerals investigation work of the Bureau of Mines, and Mr. Pope Yeatman continues in charge of the Non-Ferrous Metals Divisions of the War Industries Board.

THE NEW NATIONAL MUSEUM has been closed to the public by the board of regents, as all available space in the building has been occupied by the Bureau of War Risk Insurance. It is expected that the museum will be again opened when the new office building of the Bureau, at Vermont Avenue and H Street, is completed.

A WASHINGTON SECTION of the American Institute of Mining Engineers was organized on June 20, 1918. The officers elected were: Mr. Herbert Hoover, of the Food Administration, chairman; Dr. H. Foster Bain, of the Bureau of Mines, and Dr. David White, of the U. S. Geological Survey, vice-chairman; Mr. Harvey Mudd, secretary.

[1] Geologists, mining engineers and others interested in applied geology are invited to keep the editor informed of new investigations of mining districts or scientific studies undertaken by them, together with such other scientific and personal items as may come to their notice.

N. H. DARTON, of the United States Geological Survey, will spend August and September in New Mexico continuing his investigation of stratigraphy of the Red Beds especially as to their prospects for containing potash deposits.

WILBUR A. NELSON was elected state geologist at the meeting of the Tennessee Geological Commission held April 9. Mr. Nelson, who was formerly an assistant on the Tennessee Geological Survey, has for the past several years been engaged in private work and in mining barytes and manganese in Cartersville, Georgia. He assumed charge of the Survey on May first.

ALBERT BURCH has gone to Butte, Montana.

DR. JAMES DOUGLAS, twice president of the American Institute of Mining Engineers, and one of its principal benefactors, died in New York on June 25, 1918, at the age of eighty-one years. After a career of extraordinary activity, Dr. Douglas retired from public life, two years ago, on account of ill health. The burial took place in Quebec, and was attended by representatives of the American Institute of Mining Engineers and of the Canadian Mining Institute.

A. A. HASSAN has gone to New Brunswick, Canada, to examine manganese and pyrrhotite deposits. From New Brunswick he will go to Halifax, N. S., to make a study of the Montague gold deposits, and from there will proceed to Tangier to examine the Bradford Gold Mine.

THE West Virginia Geological Survey, Morgantown, W. Va., has just published the following works of interest. "Detailed Report on Barbour and Upshur Counties & Western Randolph," by D. B. Reger, and "Revised Figure showing Bituminous Coal Beds in West Virginia."

Professor Robert F. Griggs, of the Ohio State University, director of the Katima Expeditions of the National Geographic Society, has received a wireless message from this year's field party composed of Messrs. Jasper Sayre and Paul R. Hagelberger announcing the successful termination of the season's field work in

the Valley of Ten Thousand Smokes. The party carried the topographic survey begun last year, forward to the shore of the Bering Sea, adding some 1,500 square miles to the map and completing a section across the base of the Alaska Peninsula from Katmai Bay to Naknek. This survey will furnish the data for the construction of a topographic map on the scale of 1/250,000 of the same standard of accuracy as the work of the United States Geological Survey on maps of this scale. In the Valley of Ten Thousand Smokes, beside continuation of the general exploration and securing many valuable photographs, they succeeded in obtaining the first accurate measurement of the temperatures of the vents. For this purpose the expedition was equipped with pyrometers by the geophysical laboratory of the Carnegie Institution. They report the highest temperature measured as 430° C. Although this is subject to correction when the instruments are recalibrated on returning to the states, it probably indicates correctly the order of magnitude of the temperature of the valley. The expedition expects to return home overland *via* the Iliamna route, probably reaching Seattle about September 15.